Active Techniques for Wind and Wave Observations: Scatterometer, Altimeter (& SAR)

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ECMWF

Outline

Scatterometer Winds

- ✓ The importance of scatterometer wind observations
- ✓ Physical mechanism and wind inversion
- ✓ Data usage at ECMWF and their impact
- ✓ How we can improve the use and impact
- ✓ Concluding remarks

Altimeter Wind and Waves

- ✓ Introduction
- ✓ Verification and Monitoring
- ✓ Wave Data Assimilation
- ✓ Assessment of Model Performance (inc. Model Effective Resolution)
- ✓ Error Estimation
- ✓ Long Term Studies
- ✓ Concluding Remarks

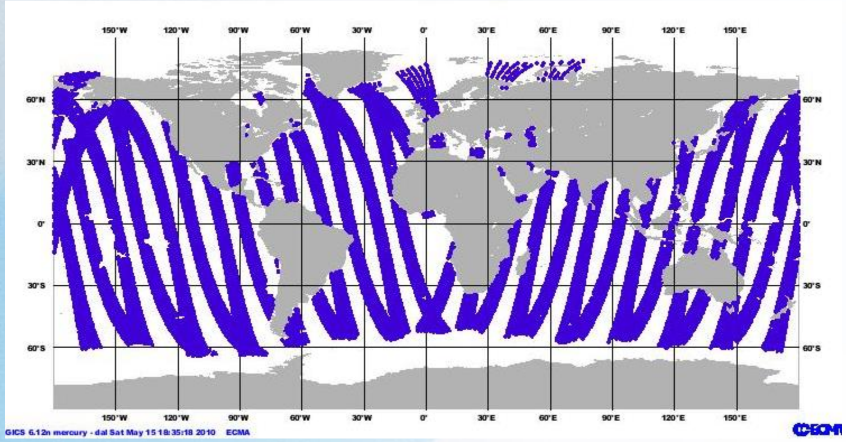
Synthetic Aperture Radar (SAR)

Why is Scatterometer important?

The scatterometer measures the ocean surface winds (ocean wind vector).

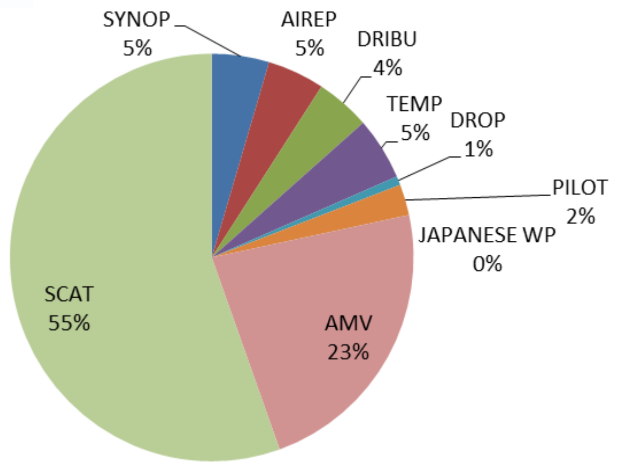
Ocean surface winds:

- affect the full range of ocean movement (from individual surface waves to complete current systems)
- modulate air-sea exchanges of heat, momentum, gases, and particulates



Wide daily coverage of ocean surface winds
Ex: 1 day of ASCAT-A data

Wind observations below 850 hPa
FSO values relative quantities (in %)



[Horanyi et al, 2013]

What is a Scatterometer?

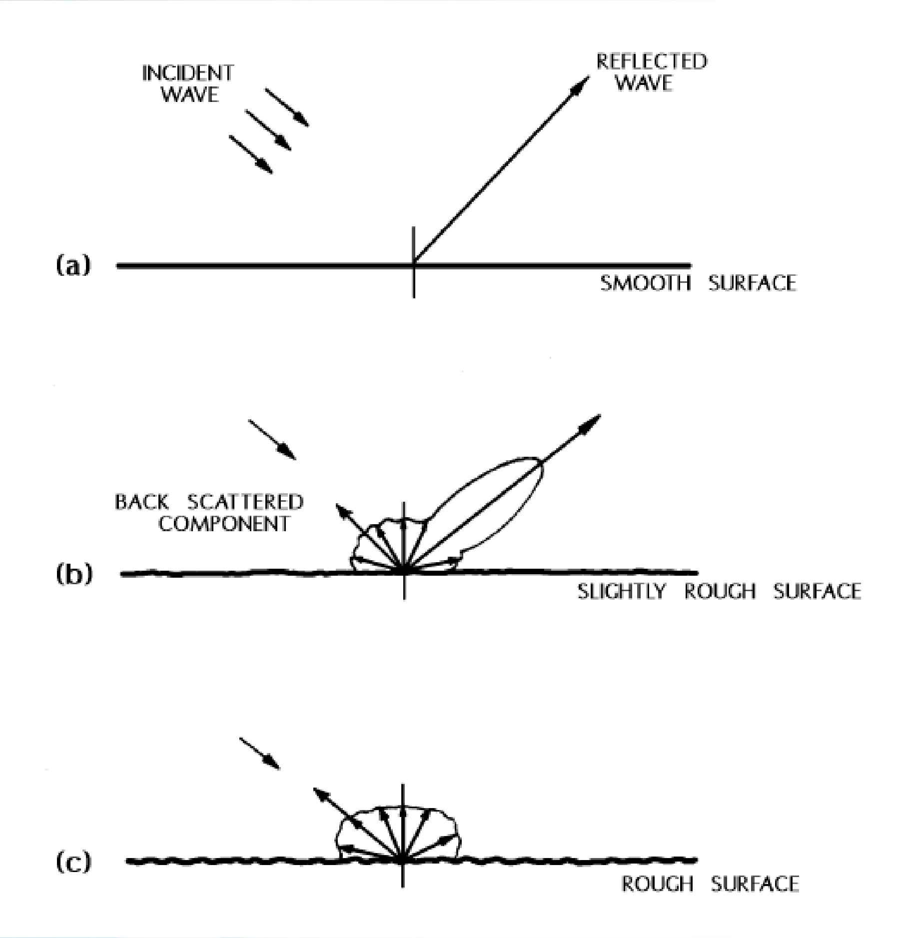
- ✓ A Scatterometer is an active microwave instrument (radar)
  - Day and night acquisition
  - Not affected by clouds
- ✓ The return signal, *backscatter* (σ_0 *sigma-nought),* which is sensitive to:
  - Surface wind (ocean)
  - Soil moisture (land)
  - Ice age (ice)

[ASCAT-A from http://www.eumetsat.int]

Scatterometer was originally designed to measure ocean winds:

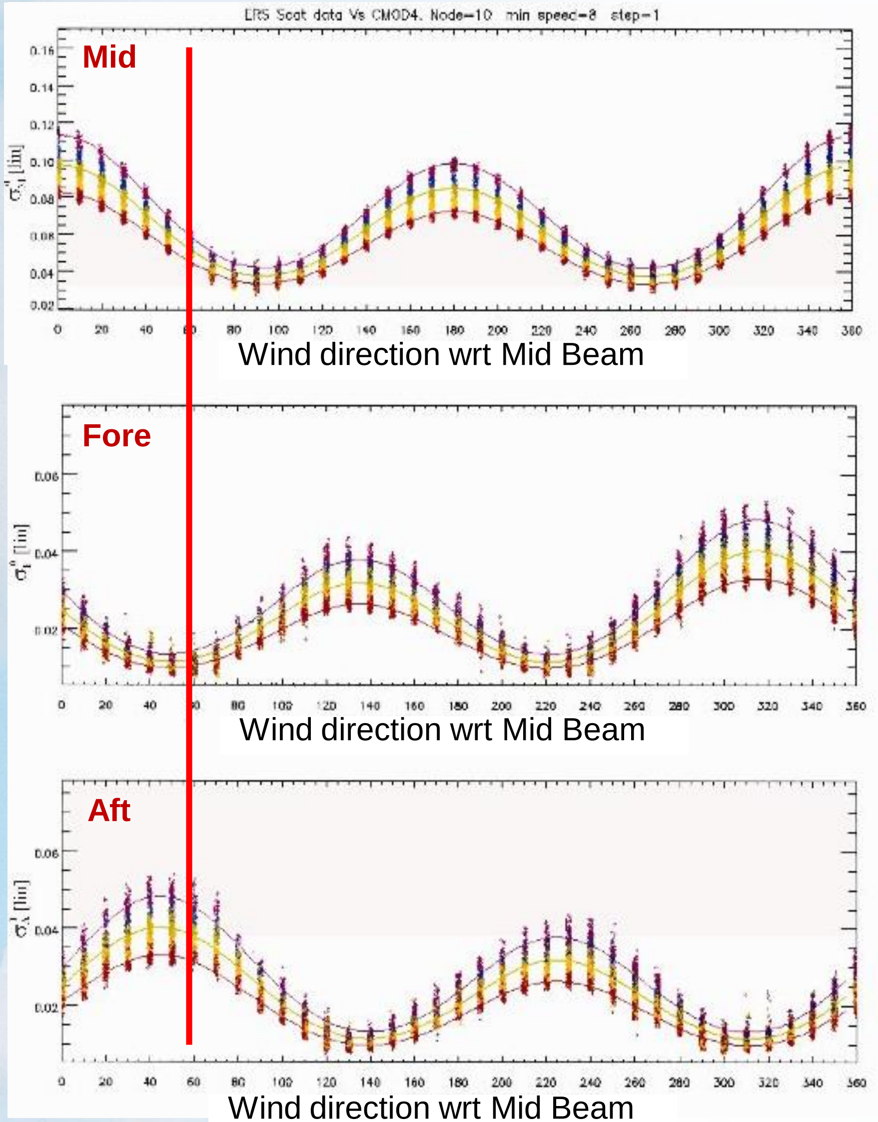
- ✓ Measurements sensitive to the ocean-surface roughness due to capillary gravity waves generated by local wind conditions (surface stress)
- ✓ Observations from different look angles: wind direction

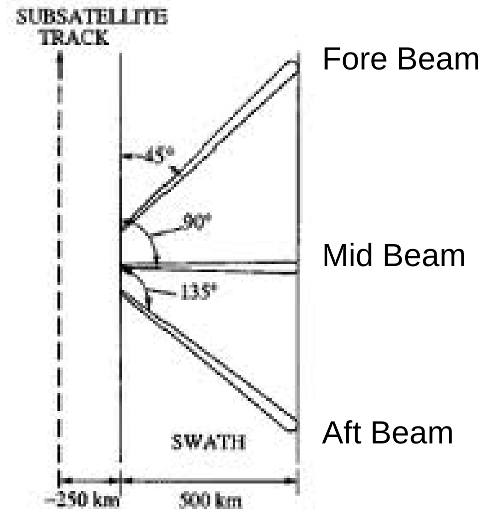
Dependency of the backscatter on... Wind speed



Dependency of the backscatter on... Wind direction

Backscatter response depends on the relative angle between the pulse and capillary wave direction (wind direction)





C-band SCAT geometry

ECMWF

How can we relate backscatter to wind speed and direction?

- ✓ The relationship is determined empirically
  - Ideally collocate with *surface stress* observations
  - In practice collocation between buoy winds and 10m model winds

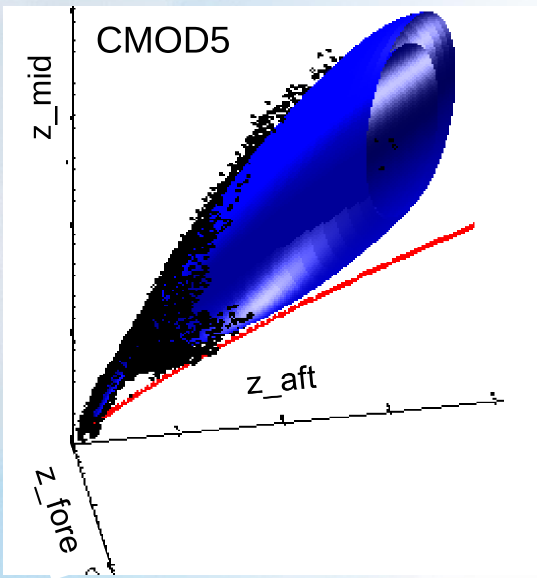
$$\sigma_0 = GMF(U_{10N}, \phi, \theta, p, \lambda)$$

U_{10N}: equivalent neutral wind speed
ϕ: wind direction w.r.t. beam pointing
θ: incidence angle
p: radar beam polarization
λ: microwave wavelength

- ✓ Geophysical model functions (GMF) families
  - C-band: CMOD
  - Ku-band: NSCAT, QSCAT

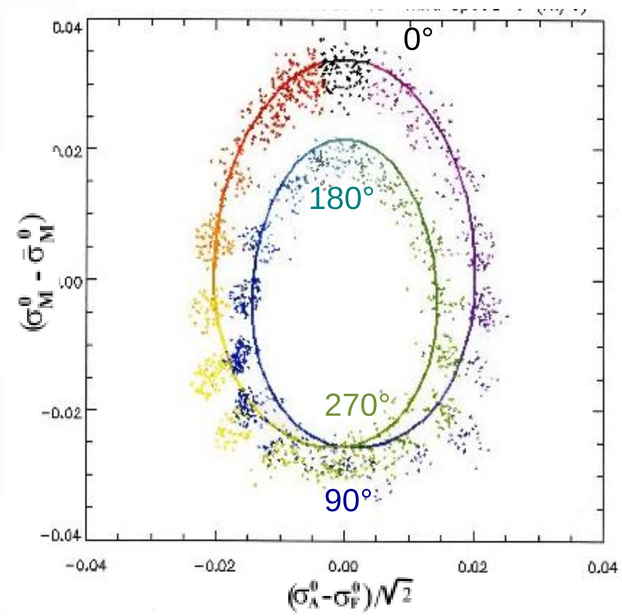
How can we relate backscatter to wind speed and direction?

For the C-band observations, σ_0 triplets lies on a double conical surface



[Stoffelen]

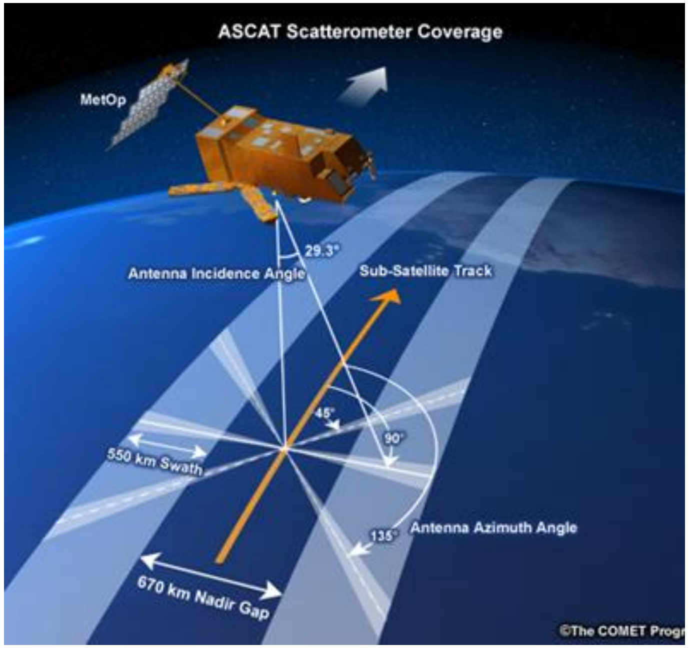
σ_0 triplets with the same wind speed



- ✓ Wind inversion: search for minimum distances between the σ_0 triplets and all the solutions on the GMF surface.
- ✓ Noise in the observations can change the position wrt the cone: wind ambiguities

C- band scatterometers

Used on European platforms (1991 onwards):
- ✓ SCAT on ERS-1, ERS-2 by ESA
- ✓ ASCAT on Metop-A, Metop-B by EUMETSAT
  - f~5.3 GHz (λ~5.7 cm)
  - VV polarization
  - Three antennae

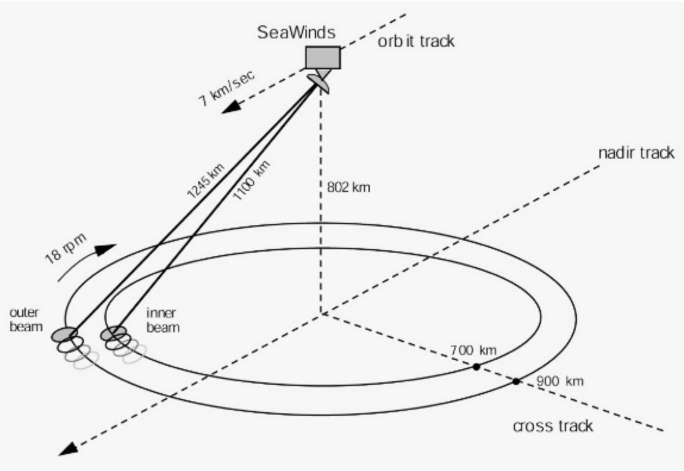


Pros and cons:
- ✓ Hardly affected by rain
- ✓ High quality wind direction (especially ASCAT)
- ✓ Two nearly opposite wind solutions
- ✓ Rather narrow swath:
  - ERS-1/2: 500km
  - ASCAT-A/B: 2x500km

Ku-band scatterometers

Used on US and Japanese platforms, later also India, China

- ✓ NSCAT, QuikSCAT, SeaWinds by NASA (and Japan)
- ✓ Oceansat by ISRO
- ✓ Haiyang-2A by China

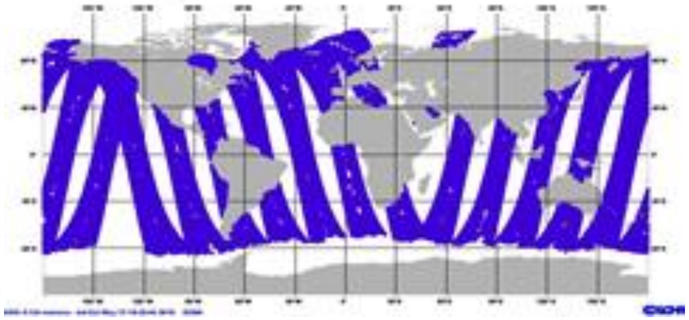


- f~13 GHz (λ ~ 2.2 cm)
- VV and HH polarization:
- Two rotating pencil-beams (4 look angles)

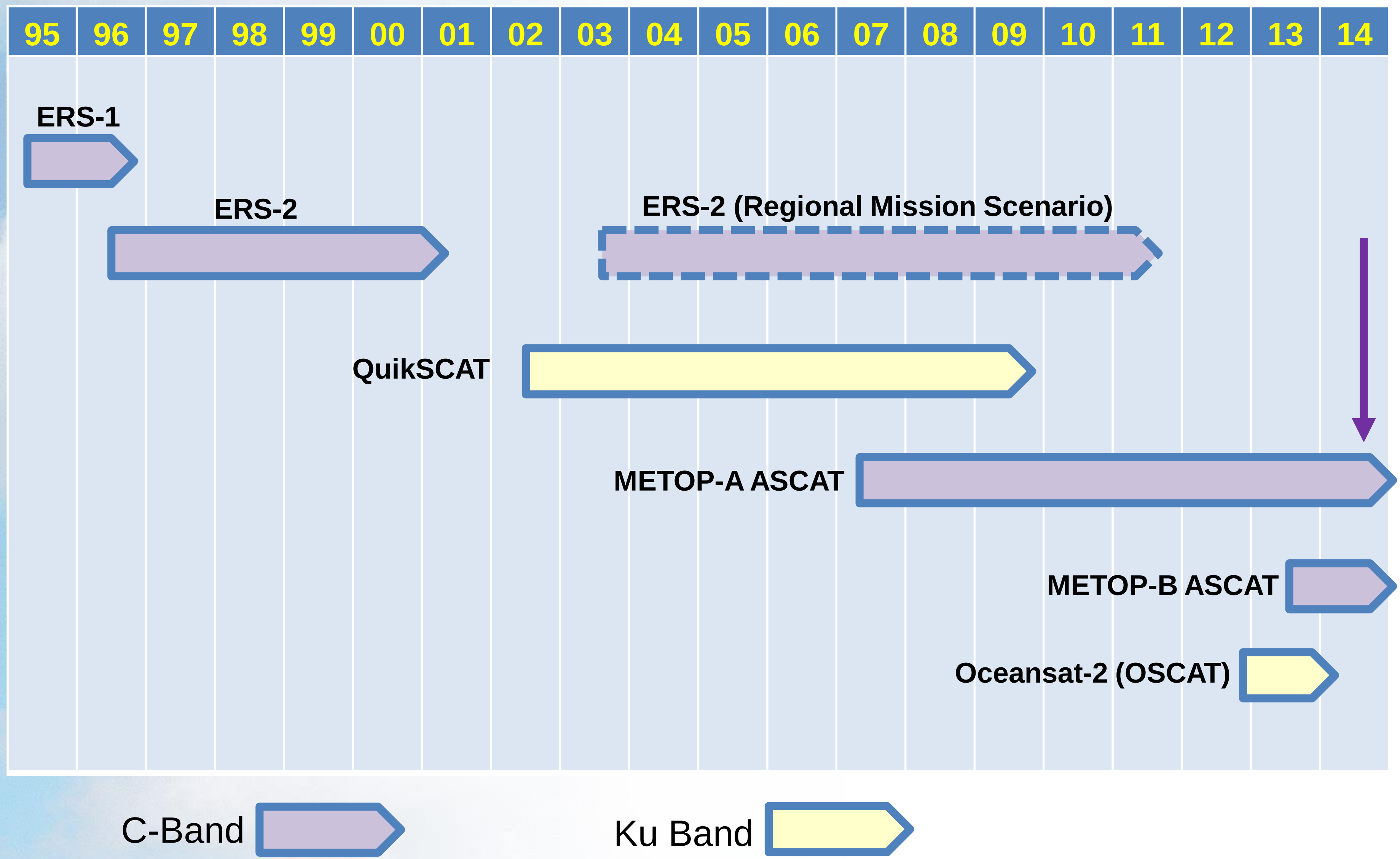
Pros and cons:

- ✓ Up to four wind solutions (rank-1 most often correct one)
- ✓ Broad swath (1,800km)
- ✓ Affected by rain
- ✓ Problems regarding wind direction:
  - azimuth diversity not good in centre of swath
  - outer 200km only sensed by one beam.

OSCAT daily coverage



Operational usage of Scatterometer winds at ECMWF

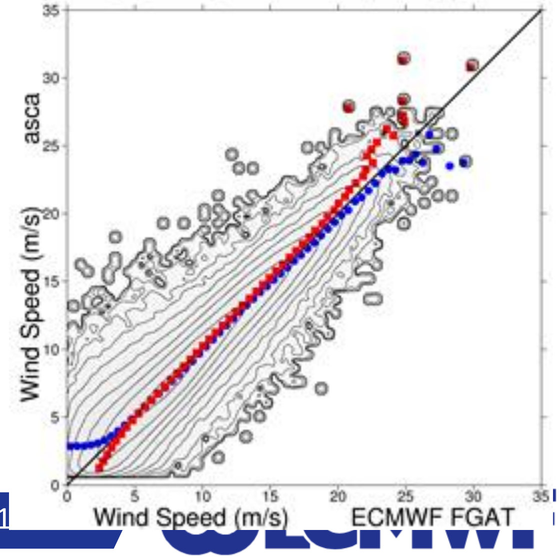


ASCAT-A & ASCAT-B assimilation strategy

ASCAT (25km) from EUMETSAT

- ✓ Wind inversion is performed in-house:
  - Sigma nought bias correction
  - Inversion using CMOD5.N
  - Wind speed bias correction
- ✓ Quality control, thinning:
  - Screening: sea ice check based on SST and sea ice data
  - Thinning: 100 km
  - Threshold: 35 m/s
- ✓ In the 4D-Var 2 solutions provided: best one chosen dynamically during the minimization
- ✓ Assimilated as 10m equivalent neutral winds
- ✓ Observation error: 1.5 m/s

ASCAT-A vs ECMWF FG Wind Speed

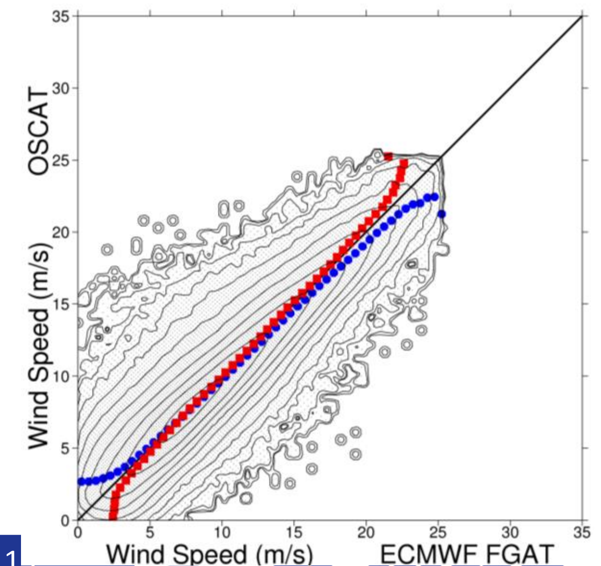


OCEANSAT-2 assimilation strategy

OCEANSAT-2 (50km)

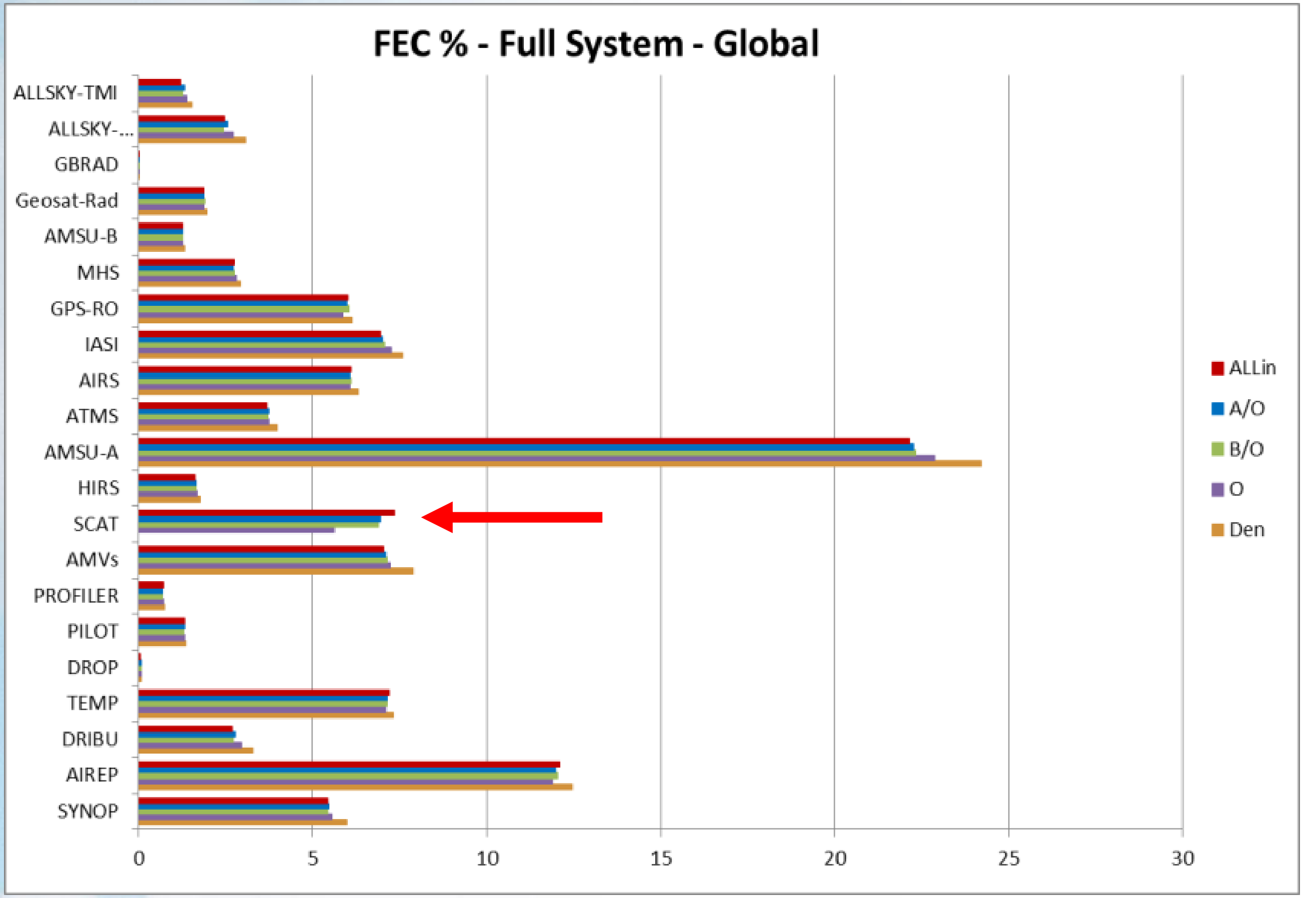
- ✓ Use of Level-2 wind products from OSI-SAF (KNMI)
- ✓ Wind speed bias correction (wind-speed dependent)
- ✓ Quality control:
  - Screening: sea ice check on SST and sea ice model
  - Rain flag
  - No thinning; weight in the assimilation 0.25
  - Threshold: 25 m/s
- ✓ Assimilated as 10m equivalent neutral winds
- ✓ Observation error: 2 m/s

OSCAT vs ECMWF FG Wind Speed



Impact of scatterometer winds

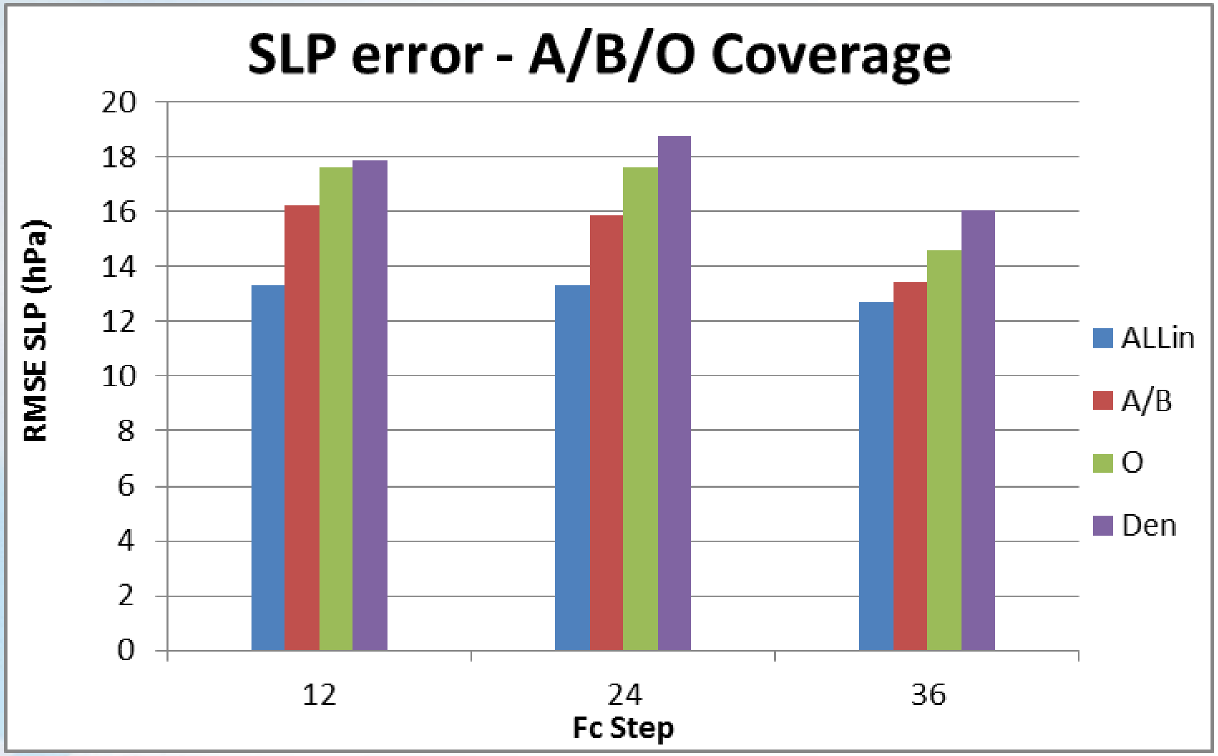
Contribution to the reduction of the 24h Forecast Error (total dry energy norm)
[Cardinali, 2009, Q.J.R.Met.Soc. 135]



Global statistics with respect to the total observing network
Dec 2012 / Feb 2013

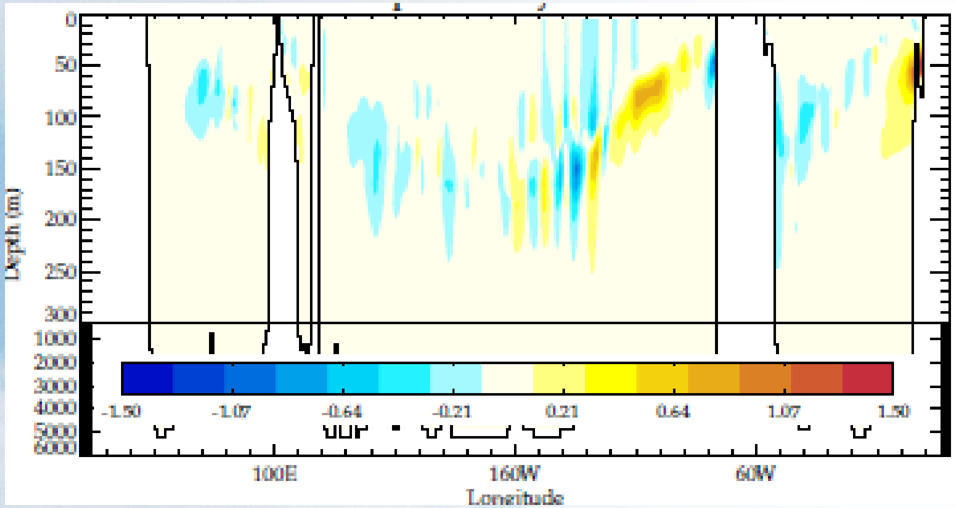
Impact of scatterometer winds
…on Tropical Cyclone FC

- ✓ For each storm the min SLP have been detected from the ECMWF model fields
- ✓ SLP have been compared to observation values (from NHC and JMA)



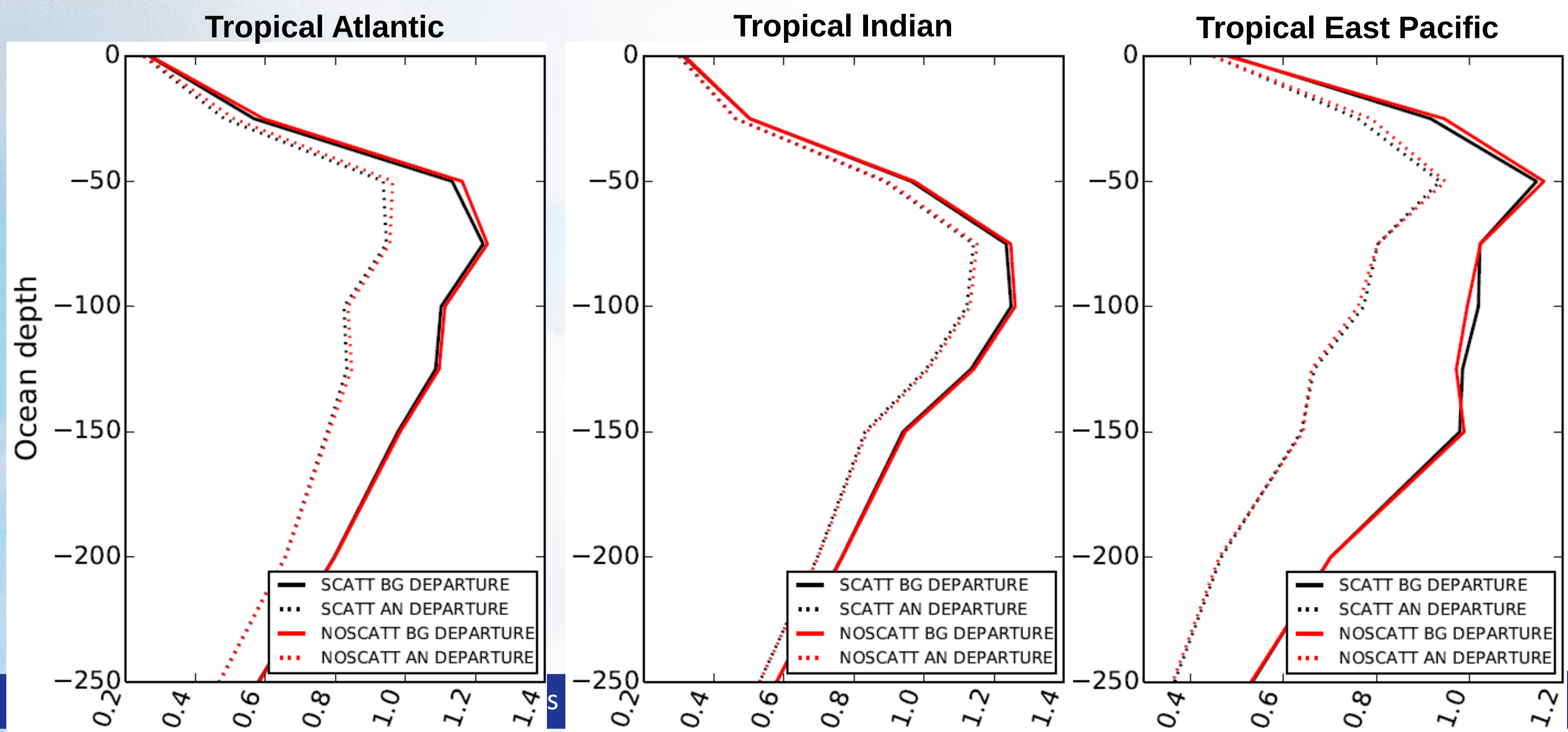
Statistics based only on cases where ASCAT-A, ASCAT-B and OSCAT passes were available
Dec 2012/ Feb 2013

Impact of scatterometer winds
...on the ocean parameters



Temperature difference Scatt – NoScatt
November 2013

Verified against conventional temperature observations

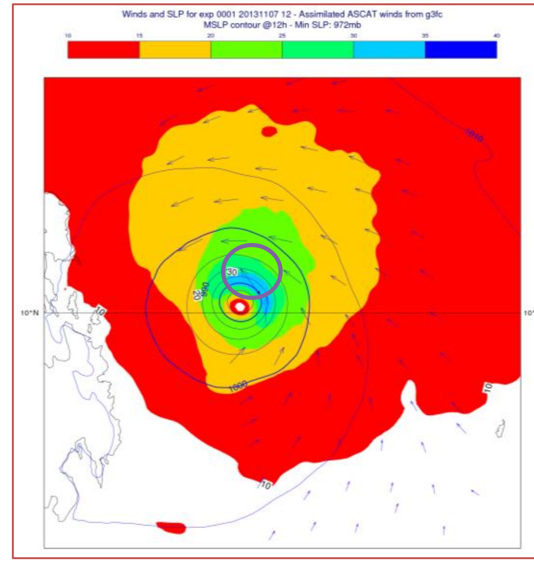


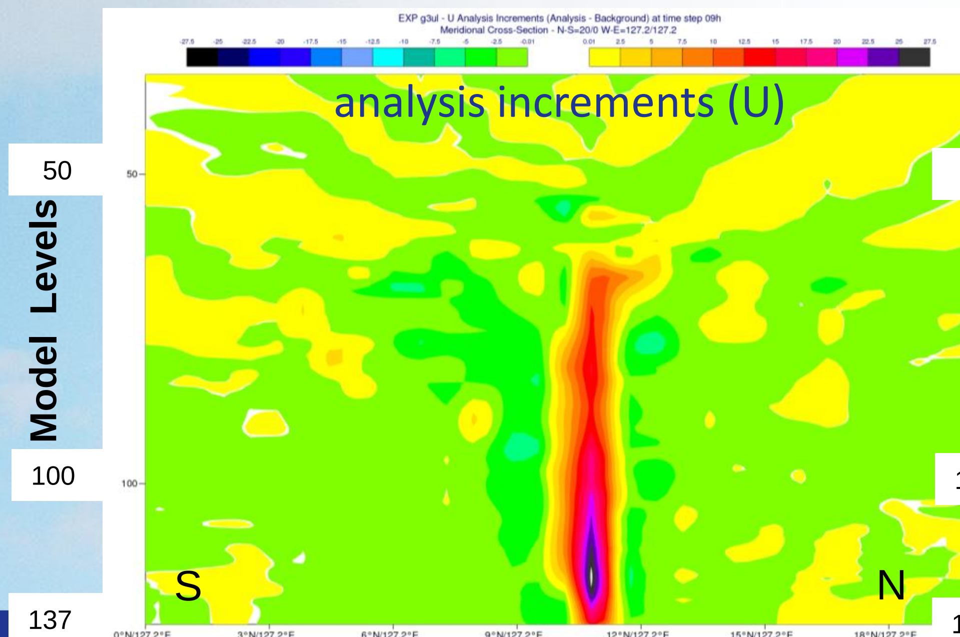
[P. Laloyaux]

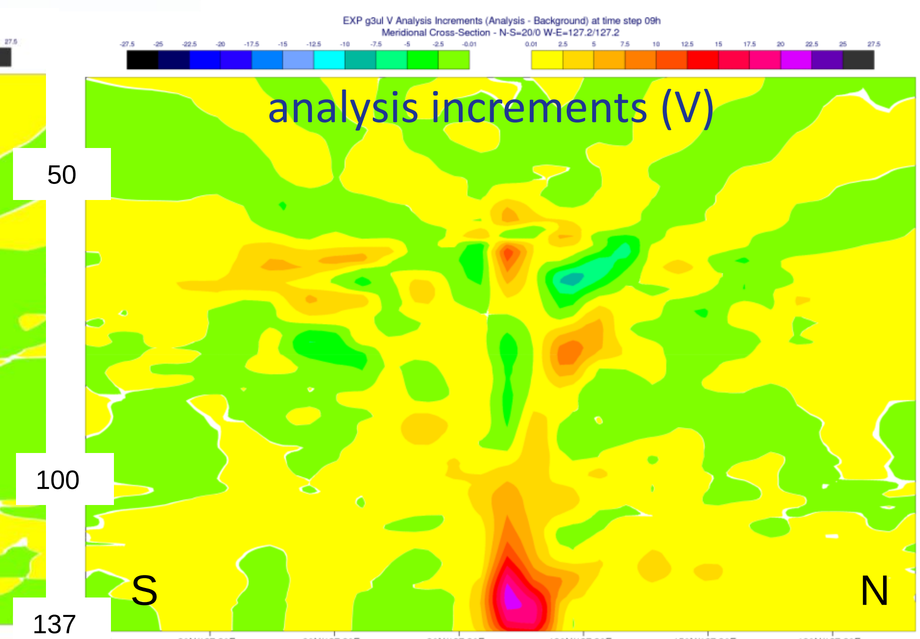
Is the model able to propagate the information?

Single Observation Experiment (1 ASCAT-A)

ML	PL(hPa)
137 ~	1013
114 ~	850
96 ~	500
79 ~	250
60 ~	100







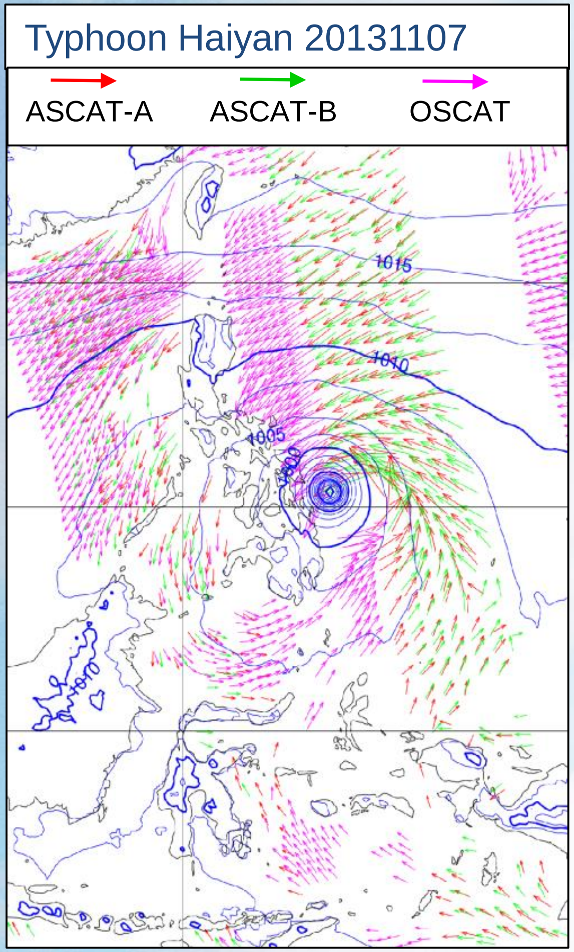
How can we improve usage and impact?

- ✓ Include dependency from other geophysical quantities such as *ocean currents*
  - Stress is related to relative wind
  - The observation operator should act on relative wind
  - Accurate ocean current input are needed

- ✓ Improve QC mostly for extreme events
  - Because of thinning and QC the strongest winds can be rejected

- ✓ Test on the observation error, thinning and use of high resolution products

Concluding remarks



Scatterometer observations widely used in NWP

- ✓ Ocean wind vectors
- ✓ Positive impact on analysis and the forecast
- ✓ Global scale and extreme events
- ✓ Available continuously from 1991 onwards

ECMWF has a long experience with scatterometry

- ✓ Assimilation since 1995
  - ERS1/2, QuikSCAT, ASCAT-A/B, Oceansat-2
  - Future missions: ASCAT-C, Oceansat-3,…
- ✓ GMF development
- ✓ Monitoring, validation, assimilation, re-calibration

On-going efforts to improve usage and impact

- ✓ Improve QC for tropical cyclones (Huber norm)
- ✓ Adapt observation errors, thinning, super-obbing
- ✓ Include dependency from other geophysical quantities

Use in the Reanalysis

- ✓ ERS1/2 and QuikSCAT in ERA-Interim
- ✓ ASCAT-A reprocessed products will be used in ERA5

Altimeter Wind & Waves

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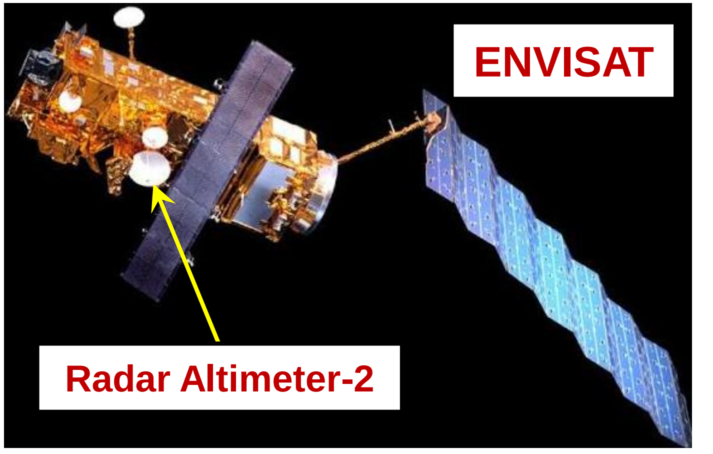
Synthetic Aperture Radar (SAR)

Introduction

Radar Altimeters



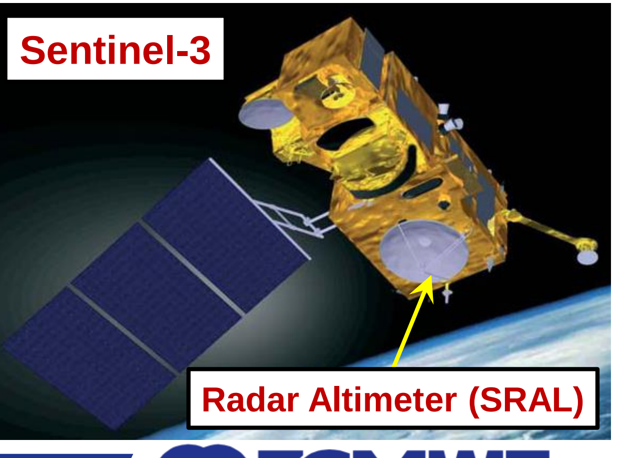
- Radar altimeter is a nadir looking instrument.
- Specular reflection.
- Electromagnetic wave bands used in altimeters:

Primary: Ku-band (~ 2.5 cm) – ERS-1/2, Envisat, Jason-1/2/3, Sentinel-3.
Ka-band (~ 0.8 cm) – SARAL/AltiKa (only example).

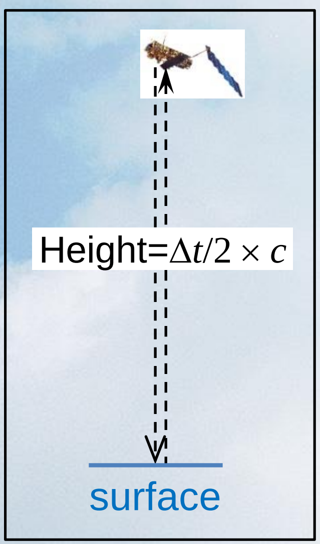
Secondary: C-band (~ 5.5 cm) – Jason-1/2/3, Topex, Sentinel-3.
S-band (~ 9.0 cm) – Envisat.

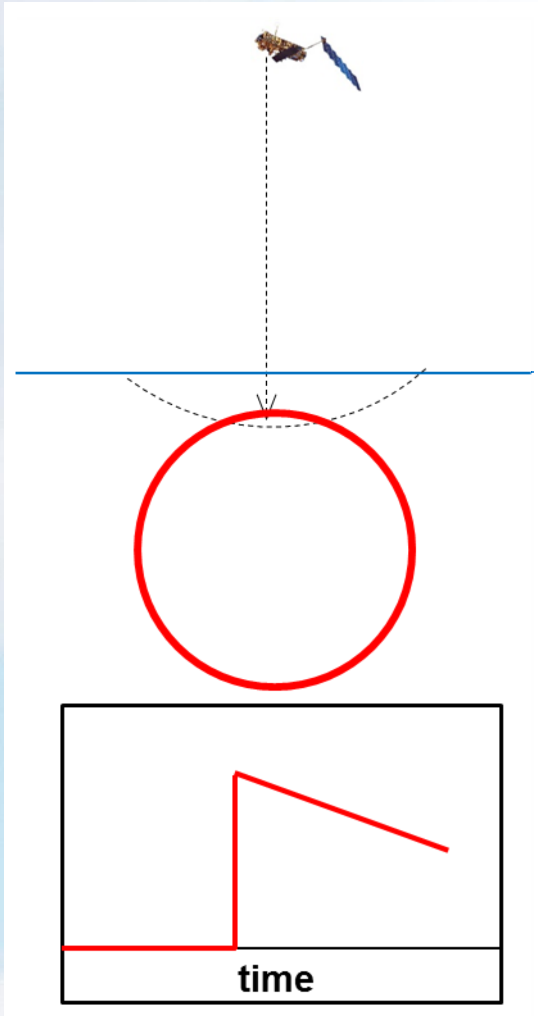
- Main parameters measured by an altimeter:

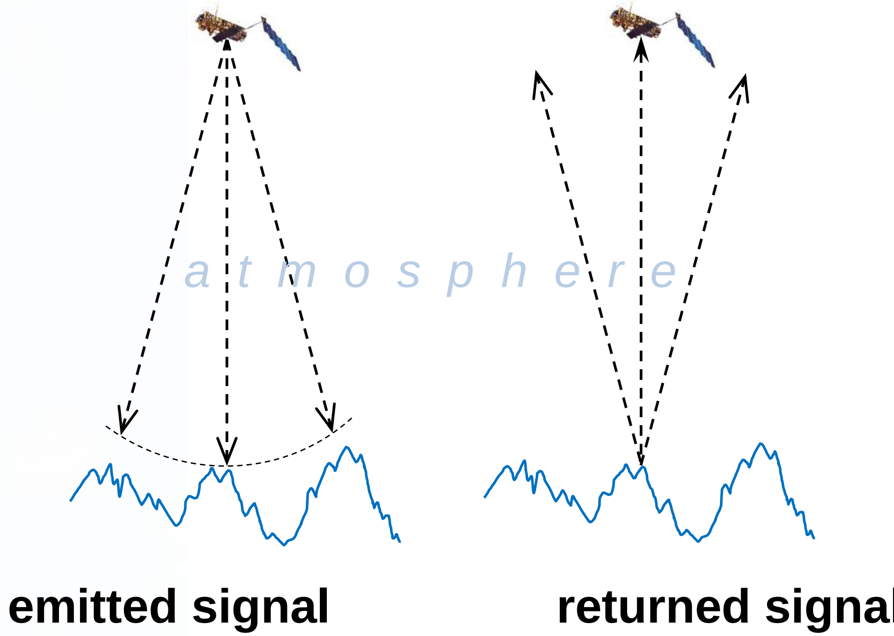
1. Sea Surface Height (ocean)
2. **Significant wave height**
3. **Wind speed**
4. Ice/land/lakes characteristics,…

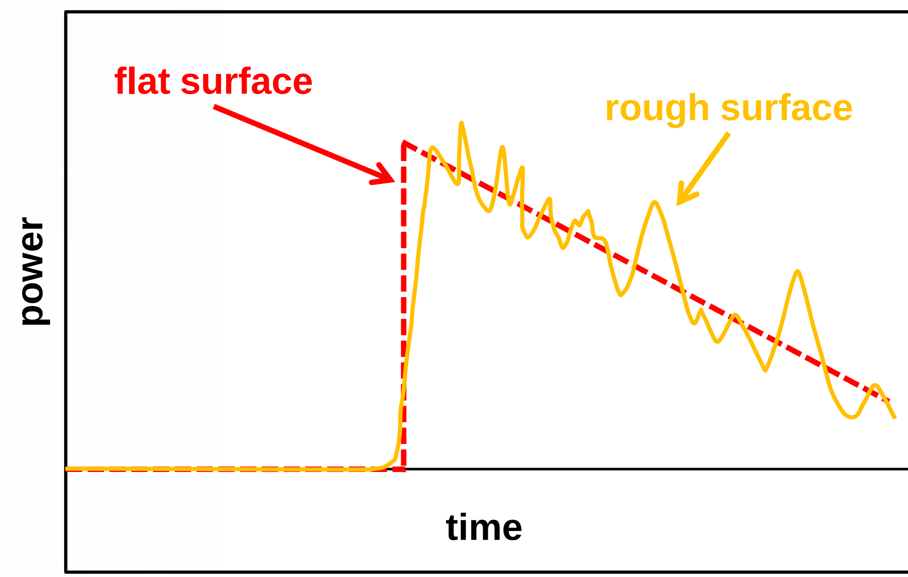


How Radar Altimeter Works:

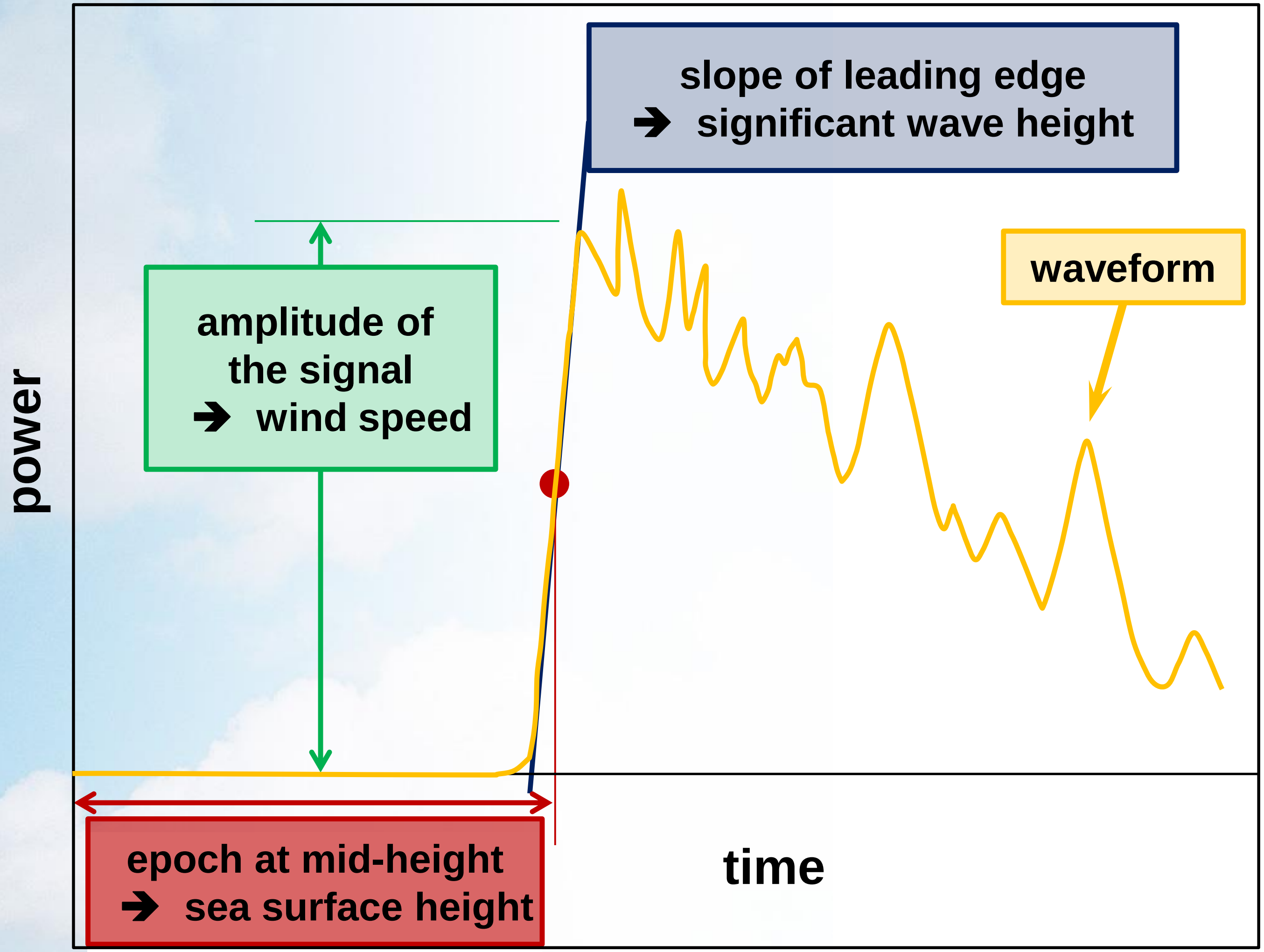






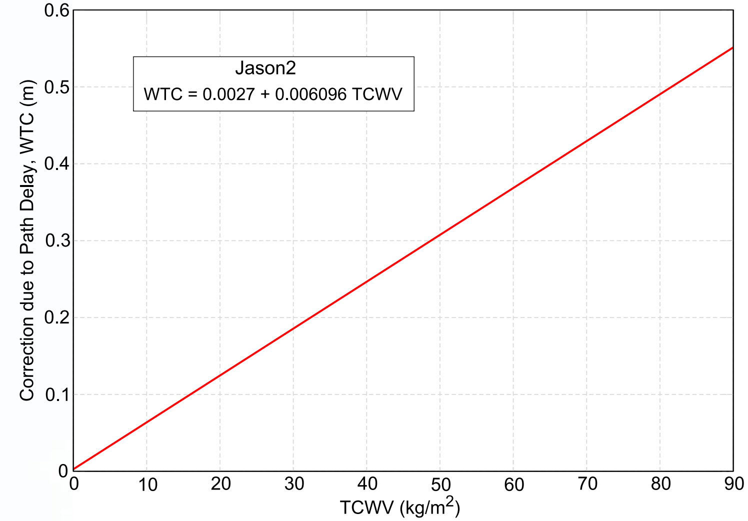


Information extracted from a radar echo reflected from ocean surface *(after averaging ~100 waveforms)*

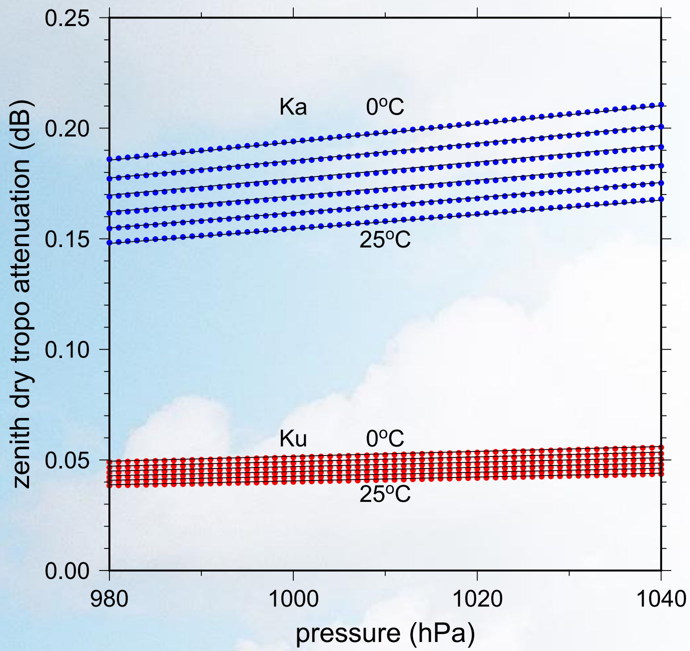


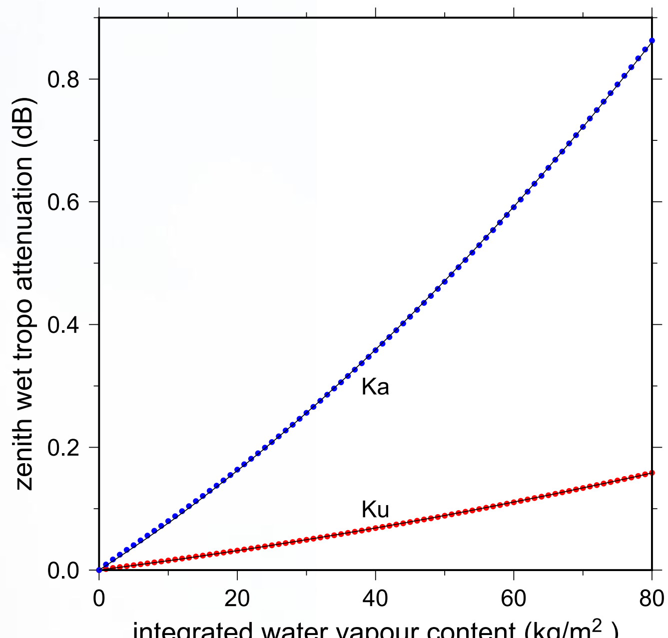
Impact of the atmosphere on Altimeter signal:

- Delay ➔ sea surface height
  - Water vapour impact: ~ 10's cm.
  - Dry air impact: ~ 2.0 m.



- Attenuation ➔ wind speed

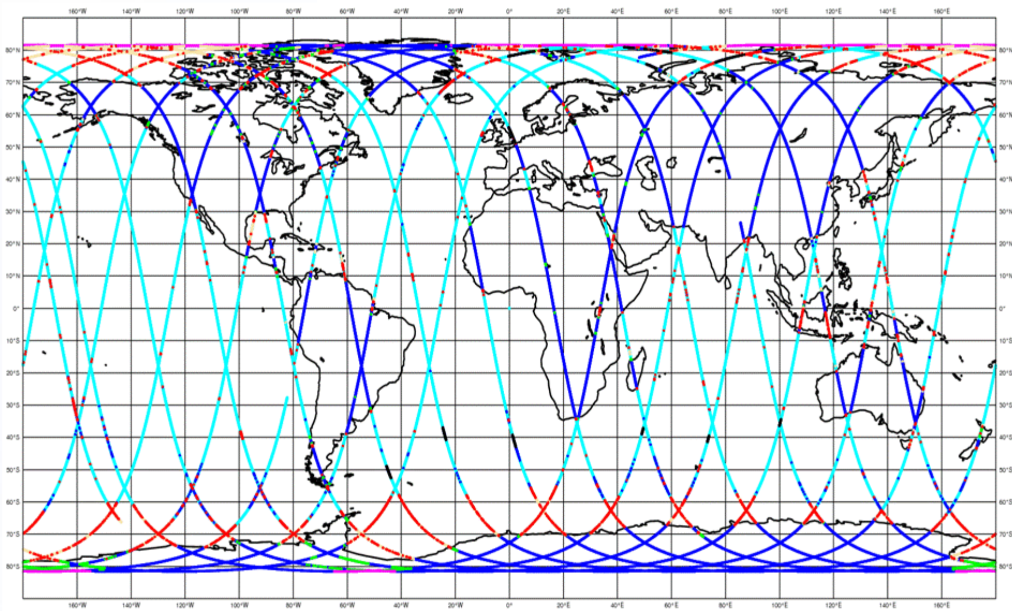




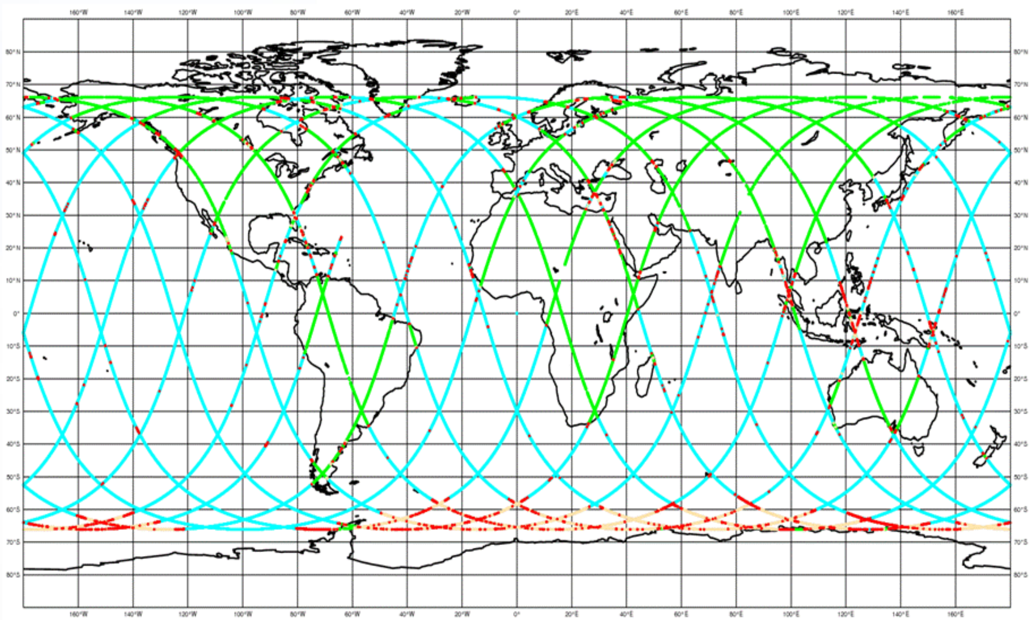
ECMWF

Typical Daily Coverage of:

Envisat/SARAL

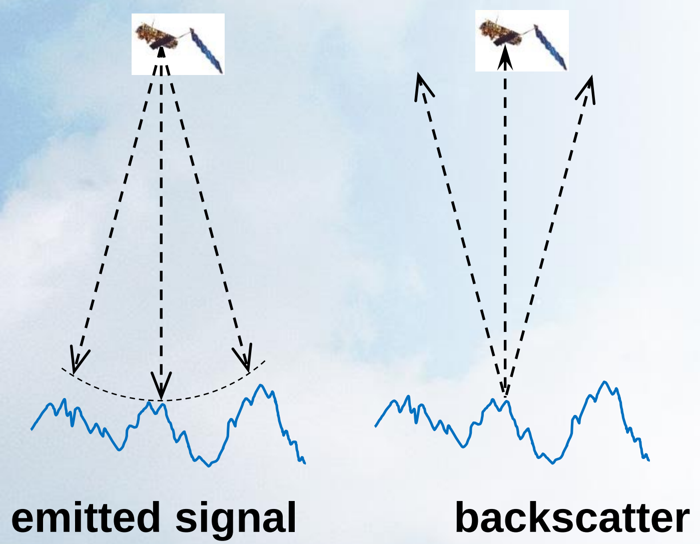


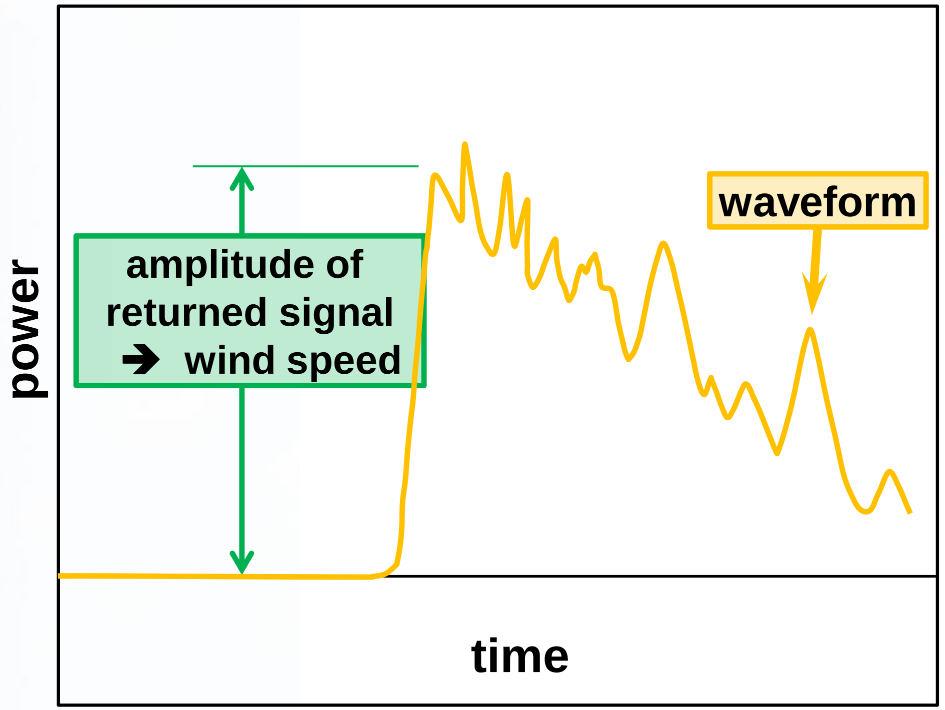
Jason-1/2



Verification & Monitoring of Altimeter Surface Wind Speed

Altimeter surface wind speed:

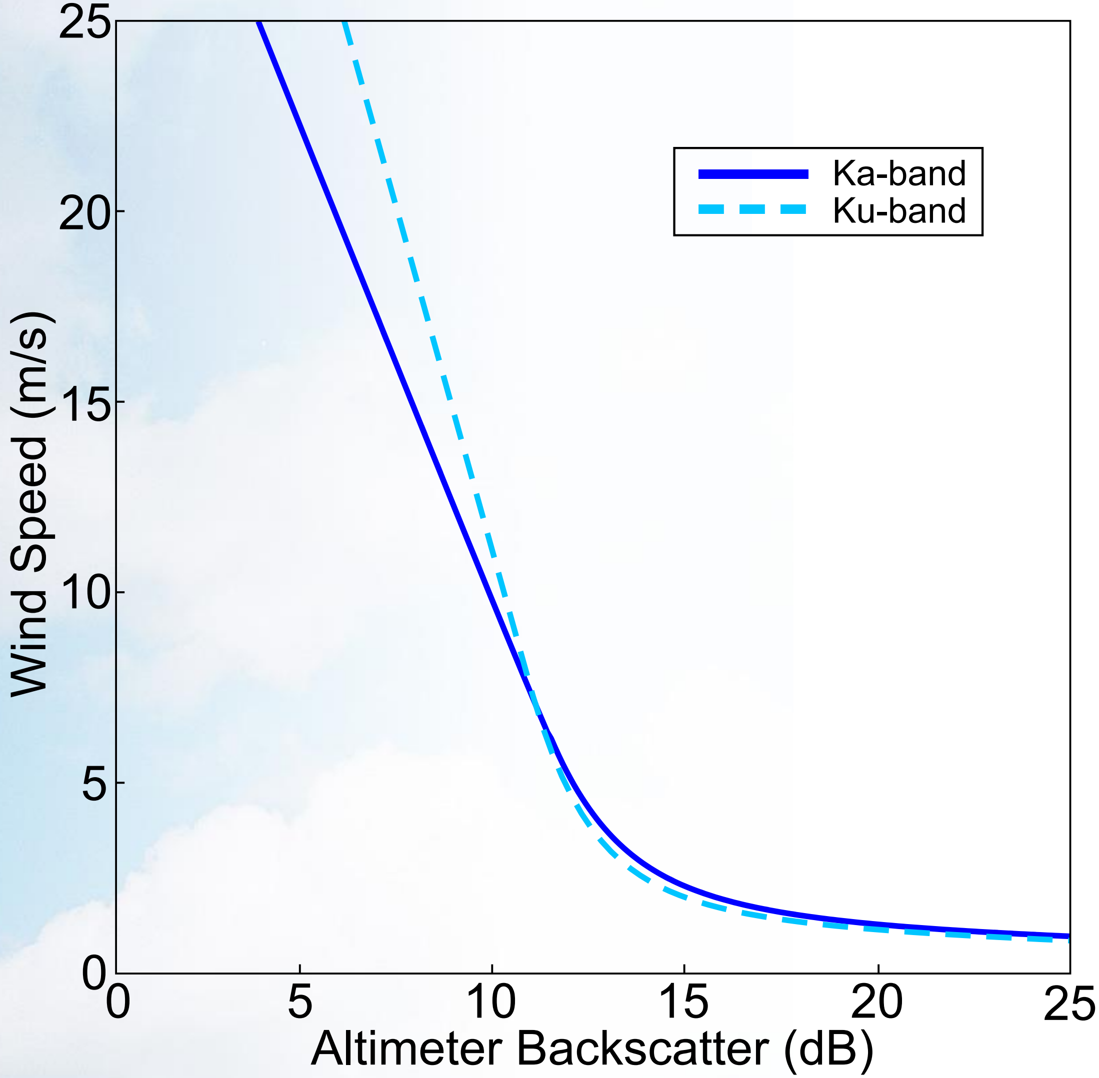




- **backscatter** is related to water surface **mean square slope (mss).**
- **mss** can be related to **wind speed.**
- Stronger wind ➔ higher mss ➔ smaller backscatter.

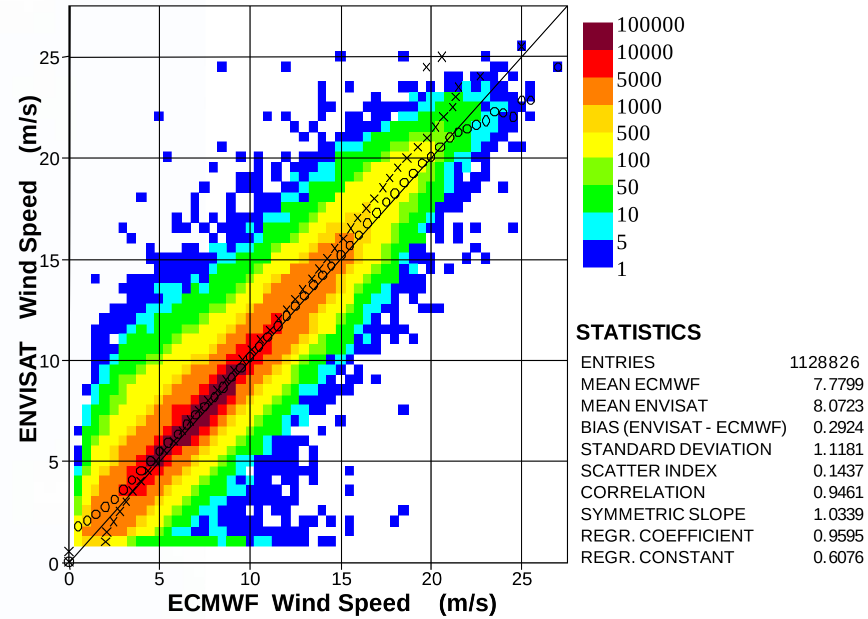
- **Errors** are mainly due to algorithm assumptions, waveform retracking (algorithm), unaccounted-for attenuation & backscatter.

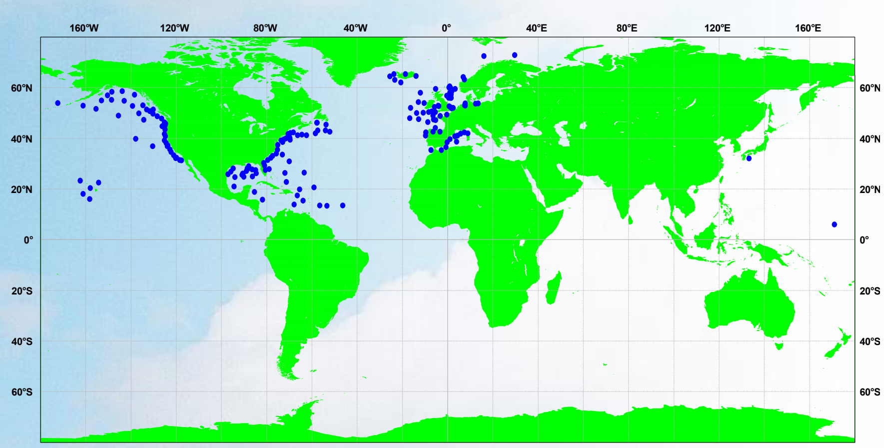
Relation between wind speed and altimeter backscatter



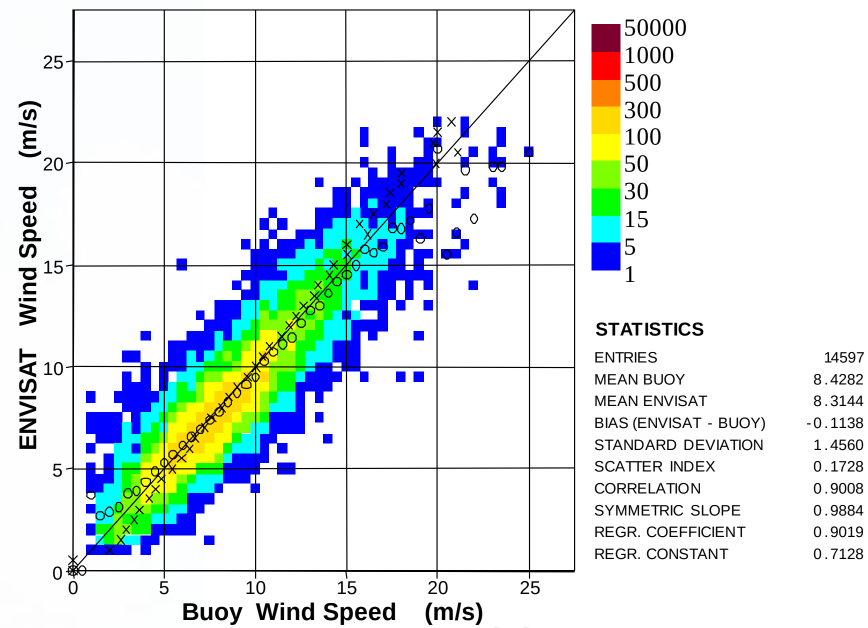
Comparison between ENVISAT NRT wind speed and ECMWF model AN (top) and in-situ measurements (bottom) for all data;

1 Jan. 2011 – 31 Dec. 2011



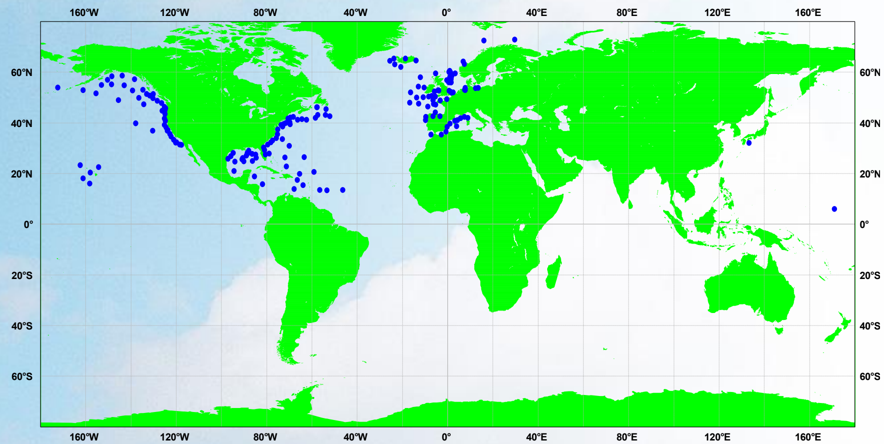


Typical locations of in-situ measurements

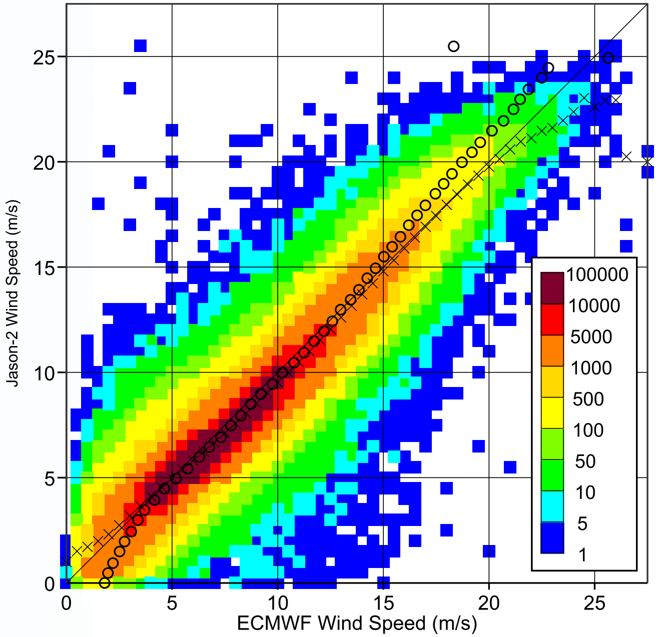


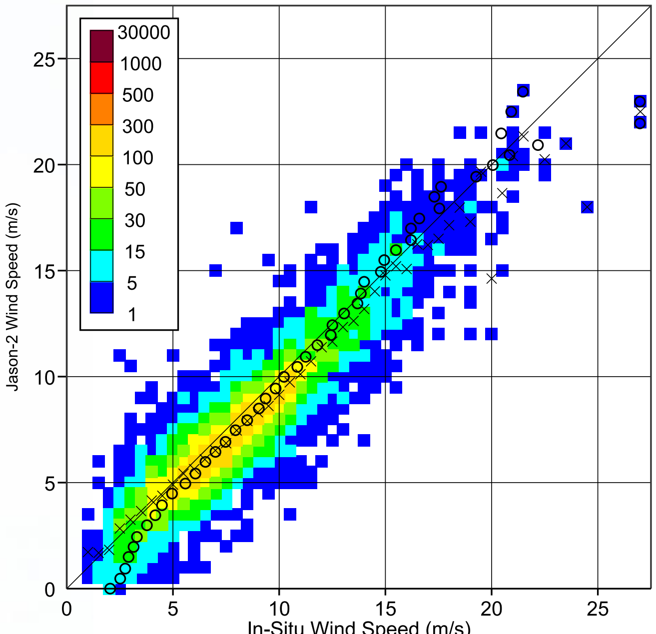
Comparison between Jason-2 NRT wind speed and ECMWF model AN (top) and in-situ measurements (bottom) for all data;

1 May 2013 – 30 April 2014



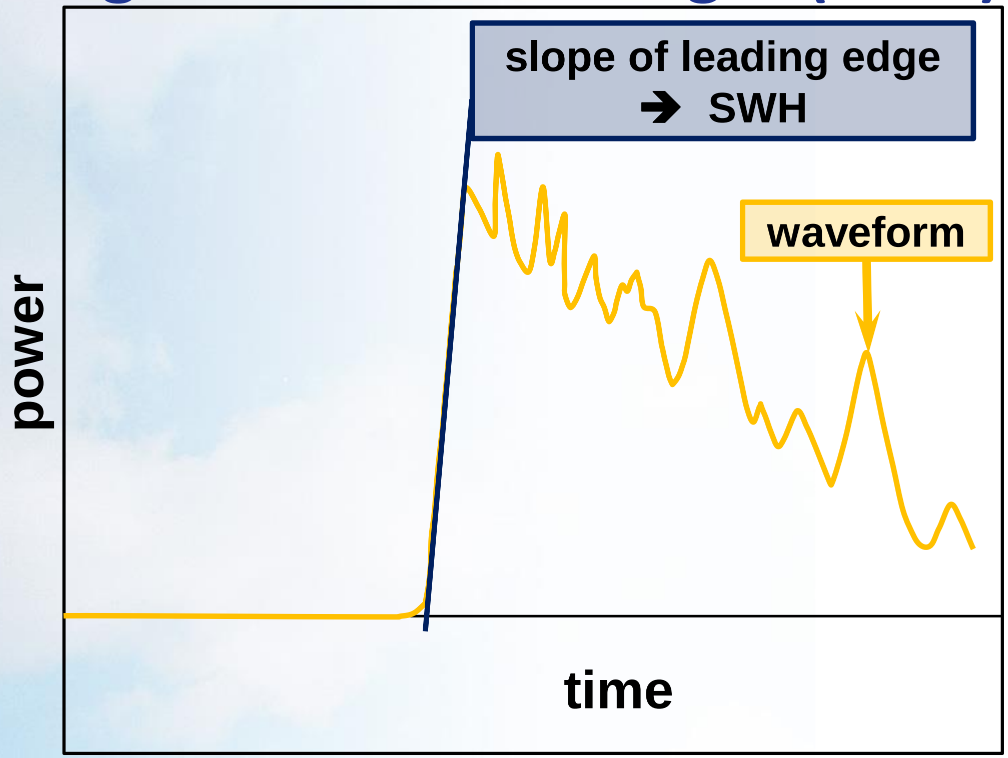
Typical locations of in-situ measurements





Verification & Monitoring of Altimeter Significant Wave Height

Altimeter Significant Wave Height (SWH)

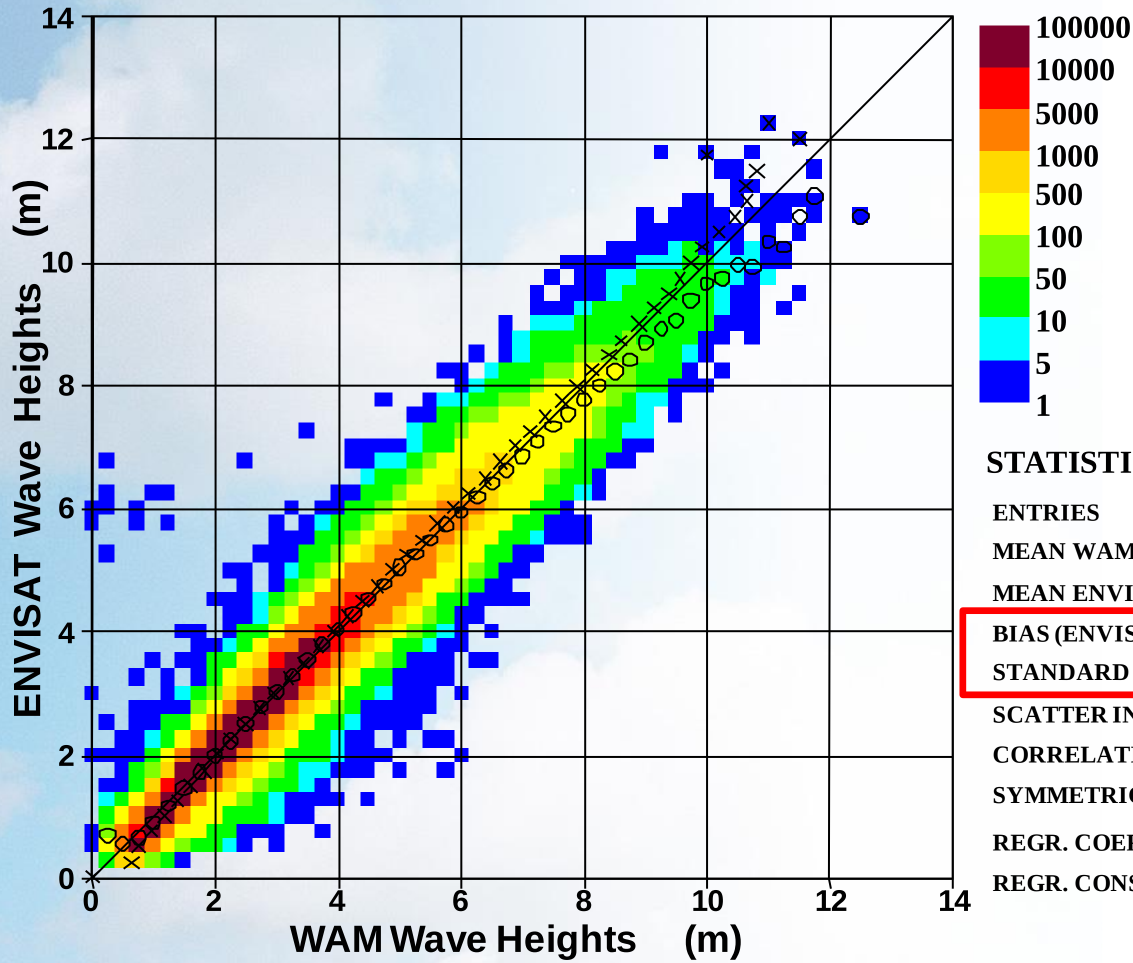


- **SWH** is the mean height of highest 1/3 of the surface ocean waves.
- Higher SWH ➔ smaller slope of waveform leading edge.

- **Errors** are mainly due to waveform retracking (algorithm) and instrument characterisation.

Global comparison between Altimeter and ECMWF wave model (WAM) first-guess SWH values

(From 02 February 2010 to 01 February 2011)

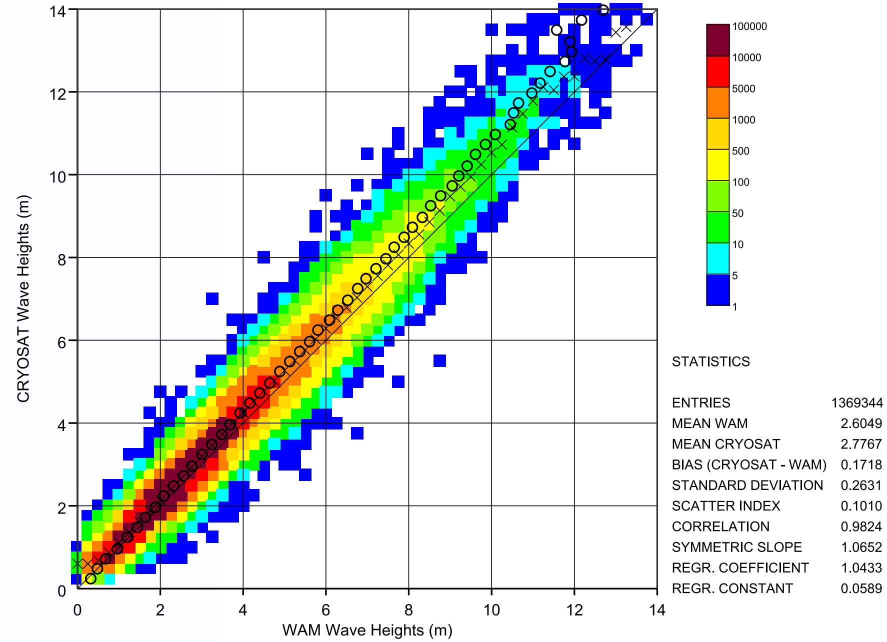


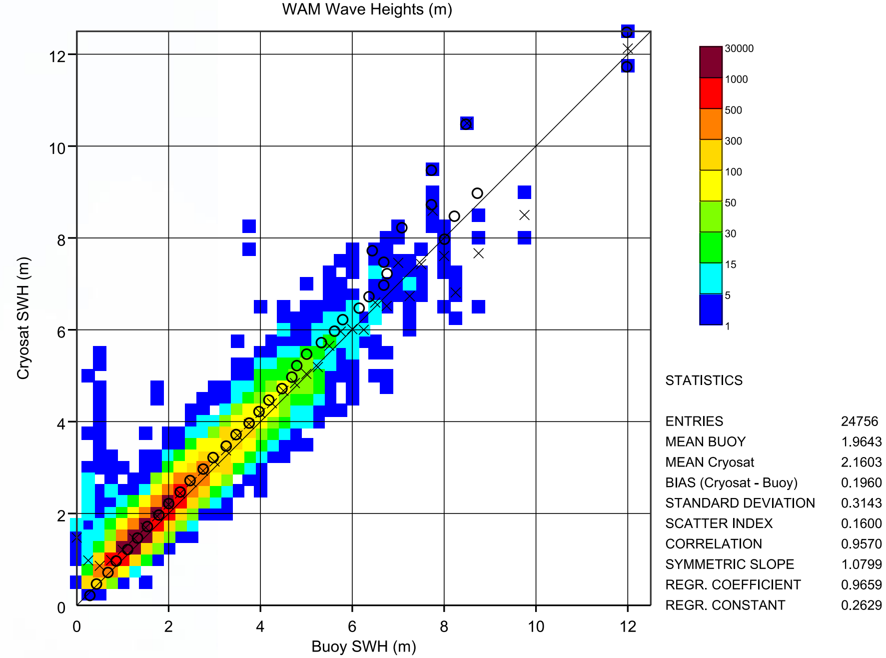
STATISTICS

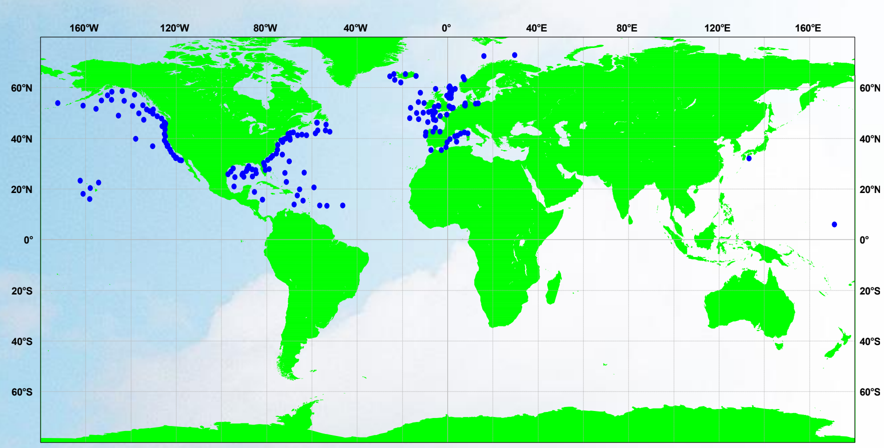
	Envisat	Jason-2	Jason-1
ENTRIES	**1125908**	1425055	1382997
MEAN WAM	**2.6014**	2.7073	2.6939
MEAN ENVISAT	**2.5851**	2.7041	2.8078
BIAS (ENVISAT - WAM)	**-0.0163**	-0.0032	0.1140
STANDARD DEVIATION	**0.2733**	0.2826	0.3232
SCATTER INDEX	**0.1051**	0.1044	0.1200
CORRELATION	**0.9786**	0.9791	0.9738
SYMMETRIC SLOPE	**1.0026**	0.9983	1.0397
REGR. COEFFICIENT	**1.0163**	0.9753	1.0025
REGR. CONSTANT	**-0.0587**	0.0637	0.1072

Comparison between Cryosat-2 NRT SWH and ECMWF model FG (top) and in-situ measurements (bottom) for all data;

1 April 2013 – 17 June 2014



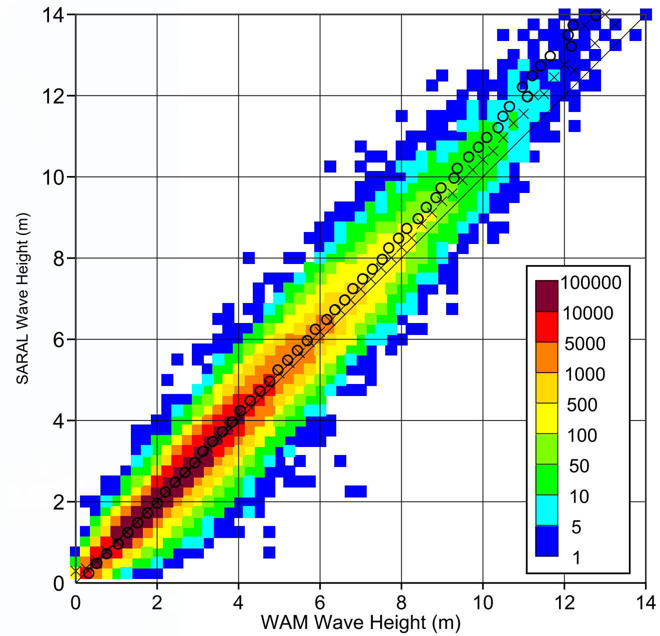


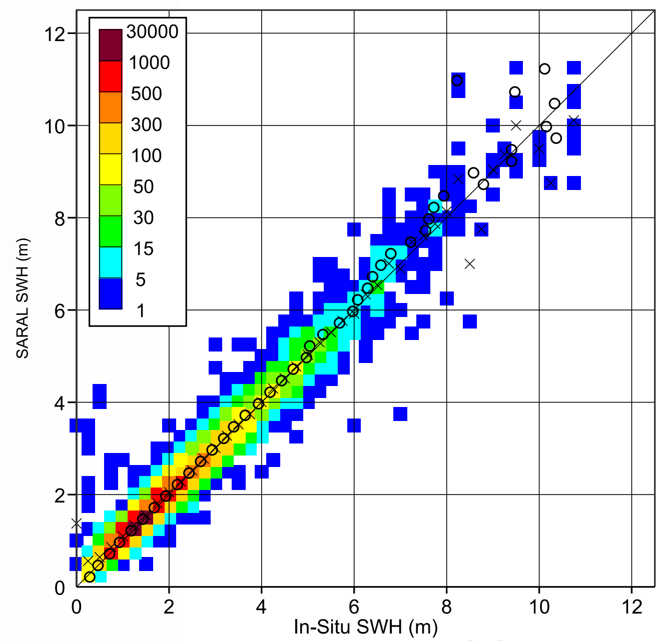


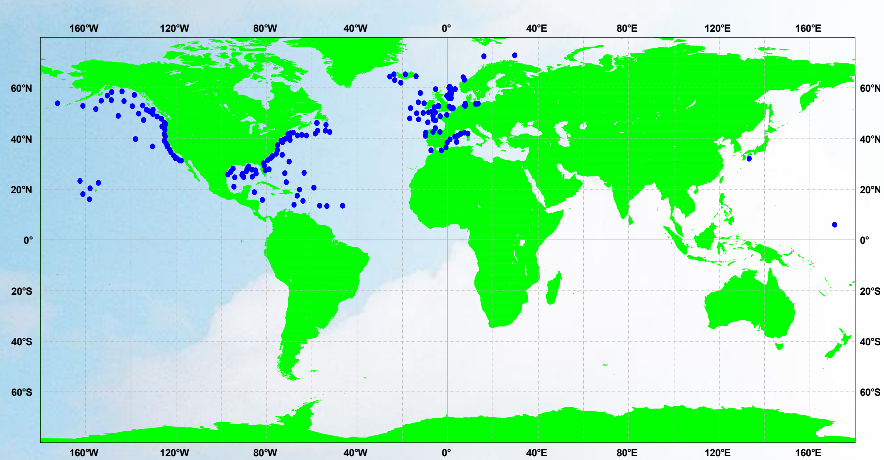
Typical locations of in-situ measurements

Comparison between SARAL (Ka) NRT SWH and ECMWF model FG (top) and in-situ measurements (bottom) for all data;

1 May 2013 – 30 April 2014







Typical locations of in-situ measurements

Assimilation of Altimeter Significant Wave Height

Data Assimilation Method

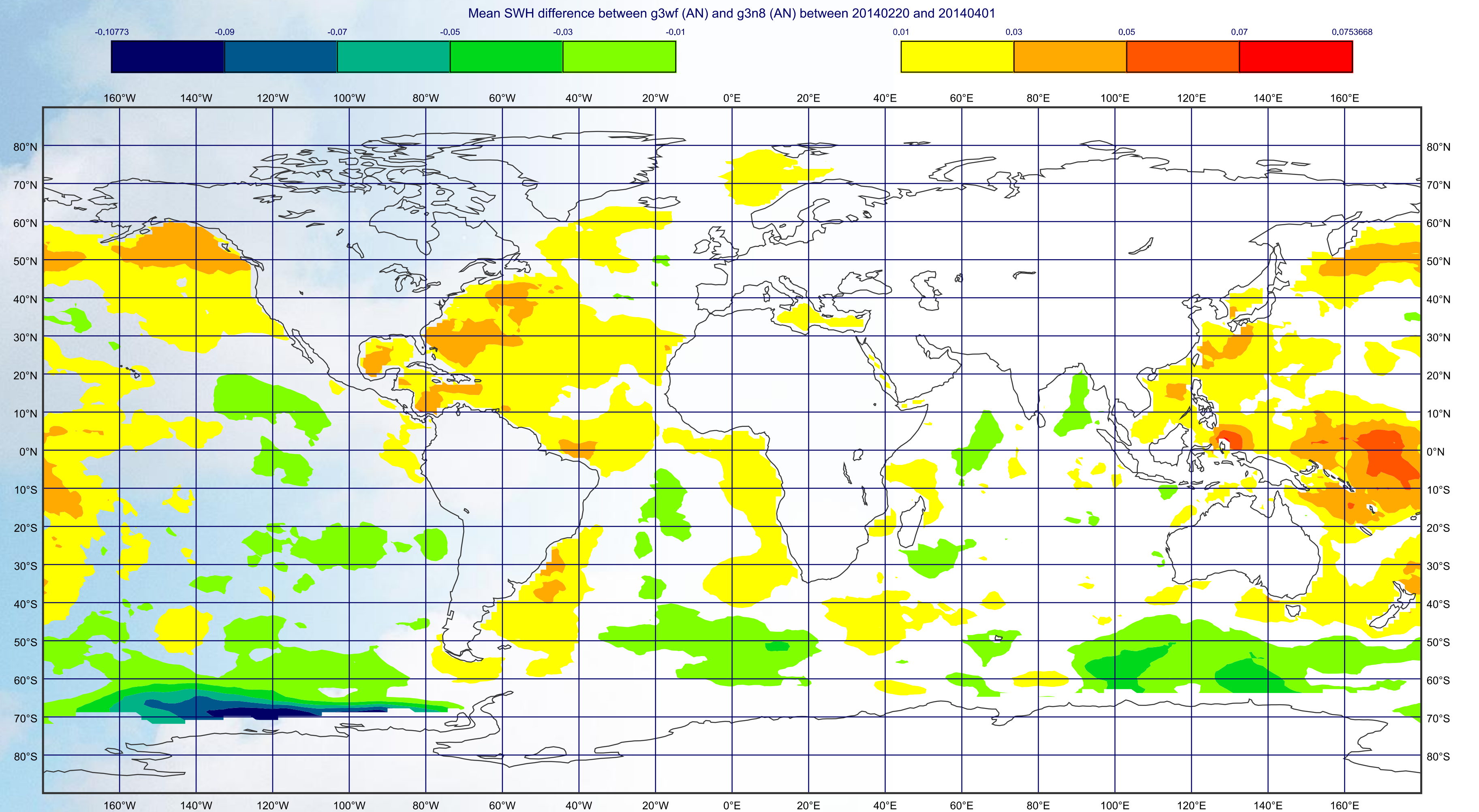
- Assimilation Method for Altimeter data:
  - Data are subjected to a quality control process (inc. super-obbing).
  - Bias correction is applied.
  - Simple optimum interpolation (OI) scheme on **SWH**.
  - The **SWH** analysis increments ➔ **wave spectrum** adjustments... (several assumptions)

Operational Assimilation of SWH

NRT Altimeter SWH operational assimilation at ECMWF:

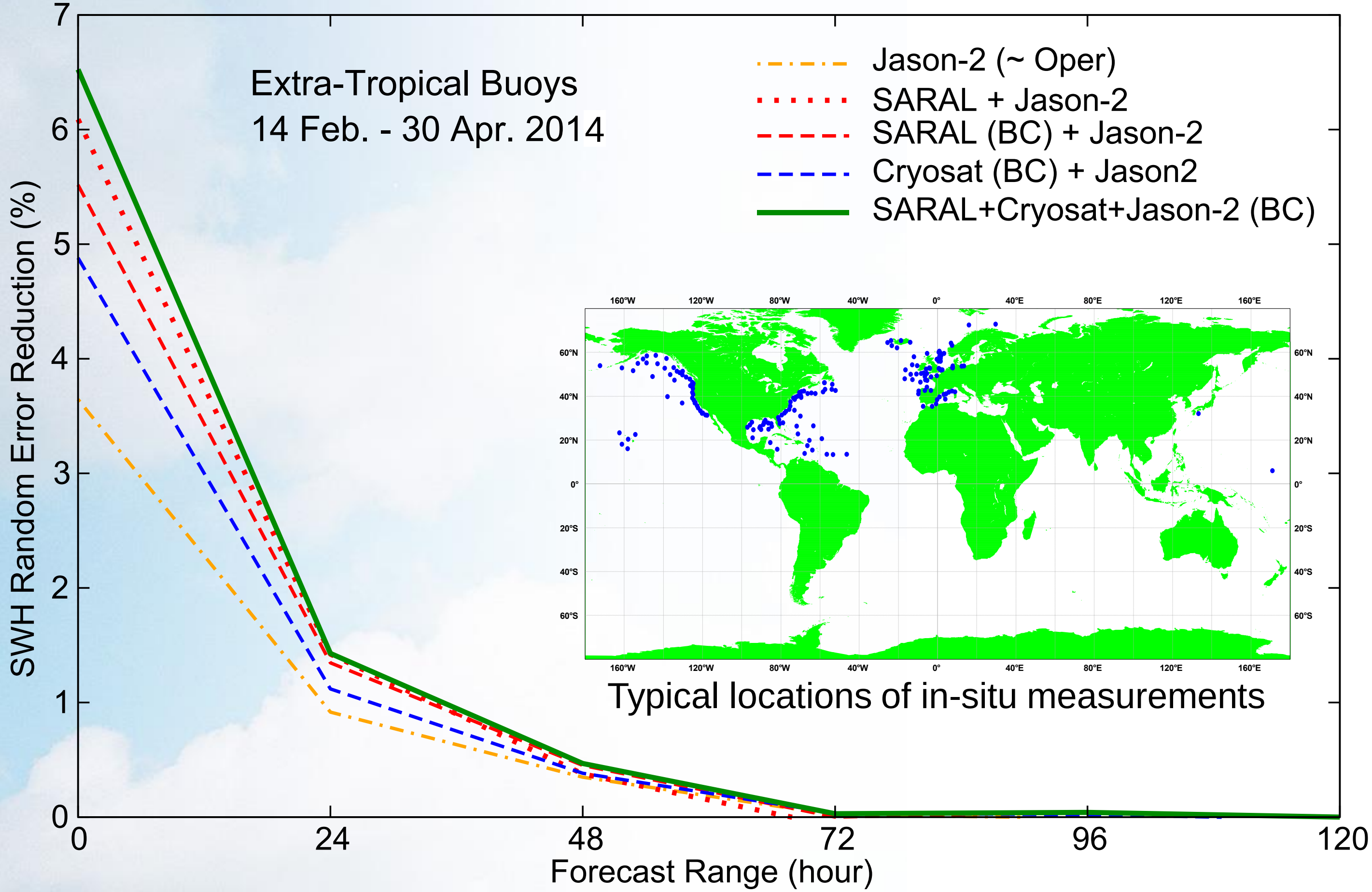
- ERS-1 URA, 15 Aug. 1993 – 1 May 1996;
- ERS-2 URA, 1 May 1996 – 23 Jun. 2003;
- ENVISAT RA-2 FDMAR, 22 Oct. 2003 – 7 Apr. 2012;
- Jason-1 OSDR, 1 Feb. 2006 – 1 Apr. 2010;
- Jason-2 OGDR, 10 Mar. 2009 – on-going;
- Cryosat-2 FDM, Coming model change (~Q4, 2014);
- SARAL OGDR, Coming model change (~Q4, 2014).

Mean impact of assimilating Cryosat-2 SWH (with BC) on SWH analysis [CS & J2] - [J2 only]

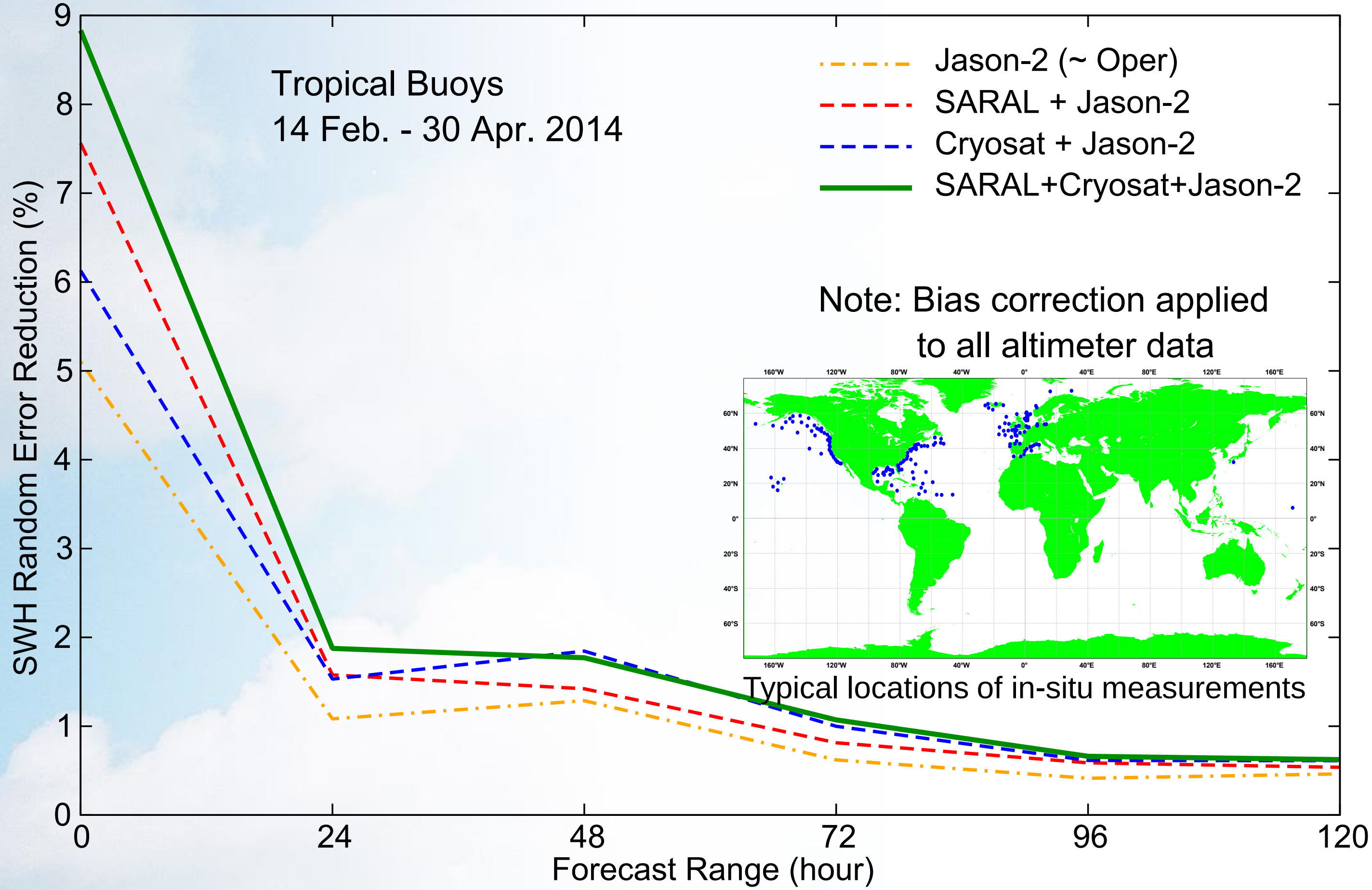


ECMWF

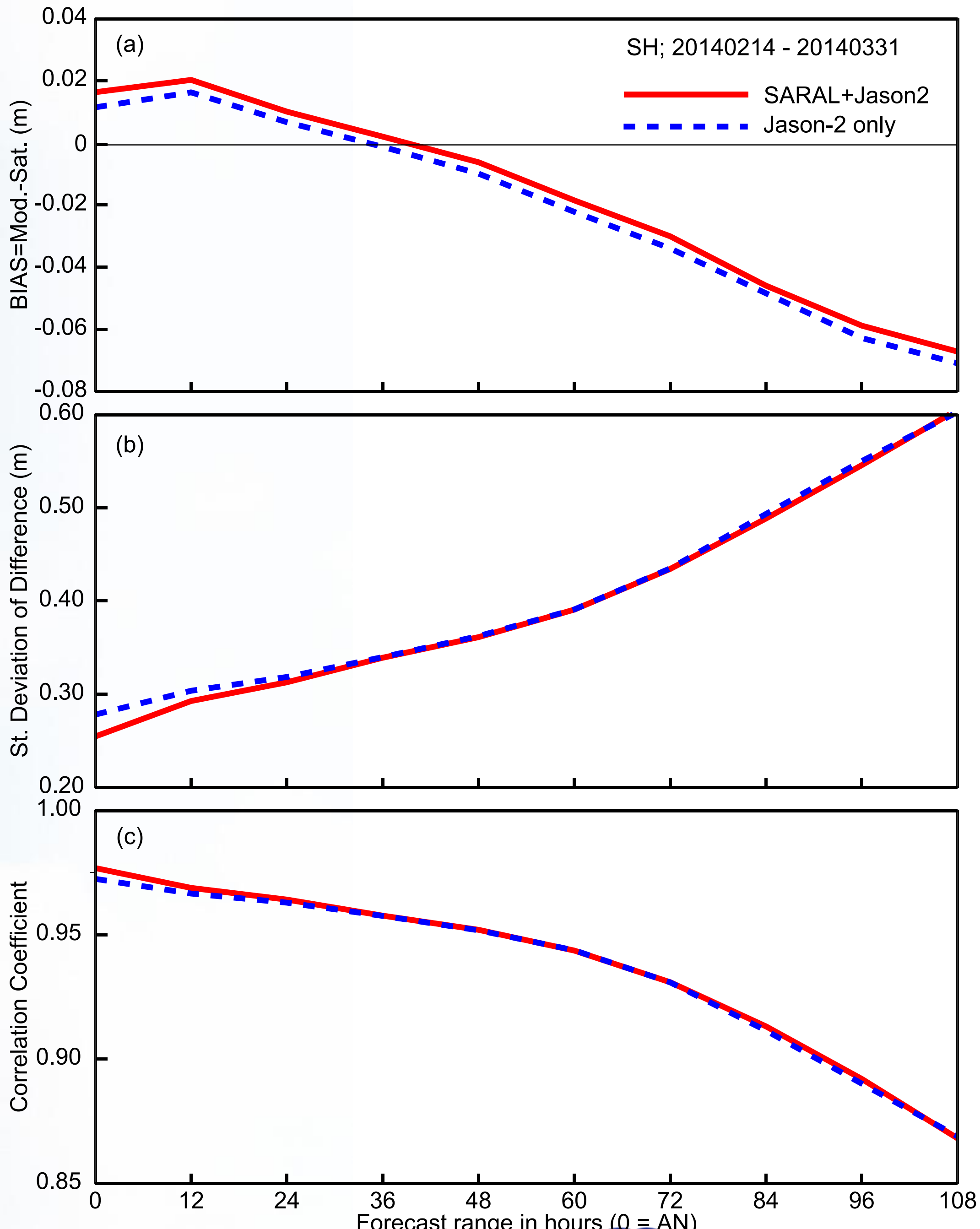
Impact of assimilating altimeter data on SWH random error as verified against Extra-tropical in-situ data, Feb. – April 2014



Impact of assimilating altimeter data on SWH random error as verified against Tropical in-situ data, Feb. – April 2014



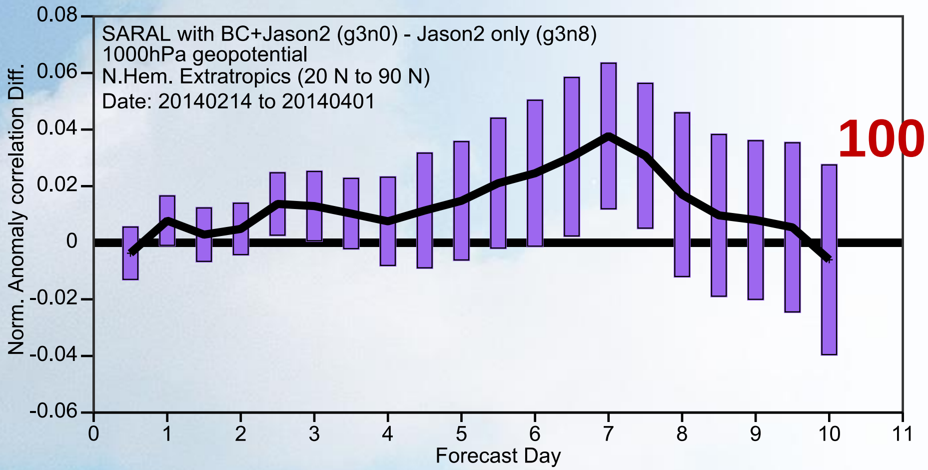
Impact of assimilating SARAL data on SWH error as verified against Cryosat -2 SWH, Feb. – March 2014

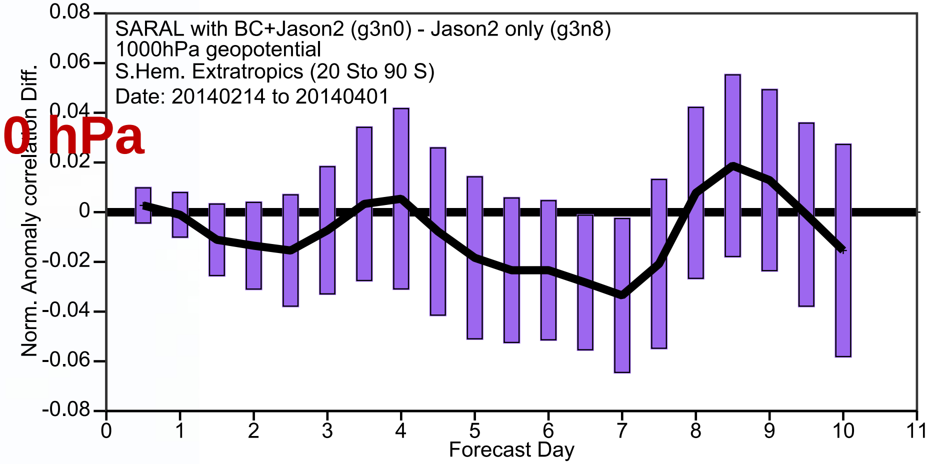


Mean Impact of using SARAL (with BC) SWH on Geopotential anomaly correlation (bars @ 95% level)

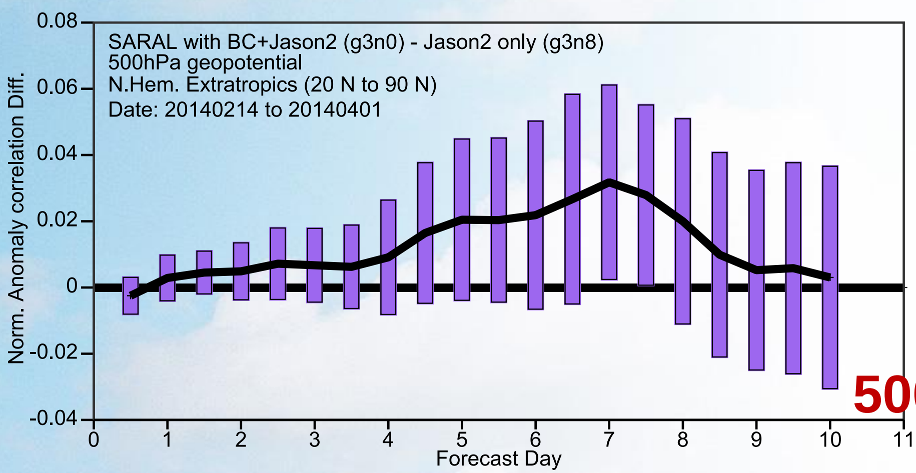
Northern Hemisphere

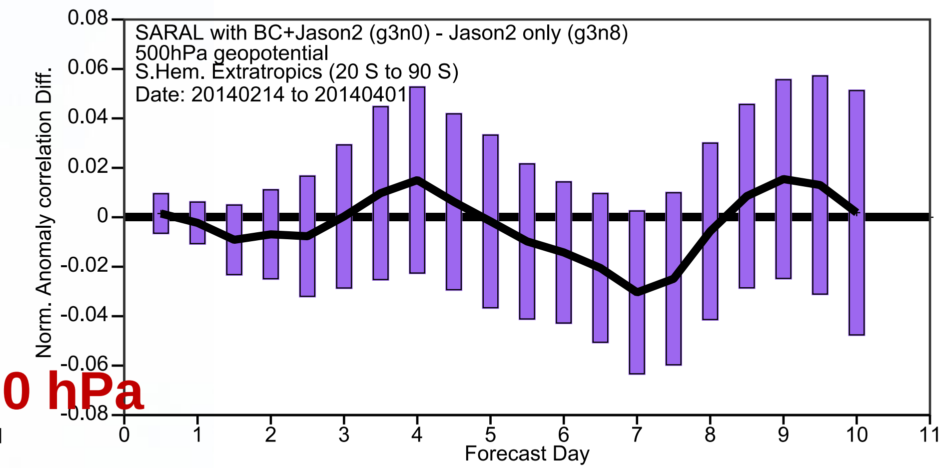
Southern Hemisphere





1000 hPa

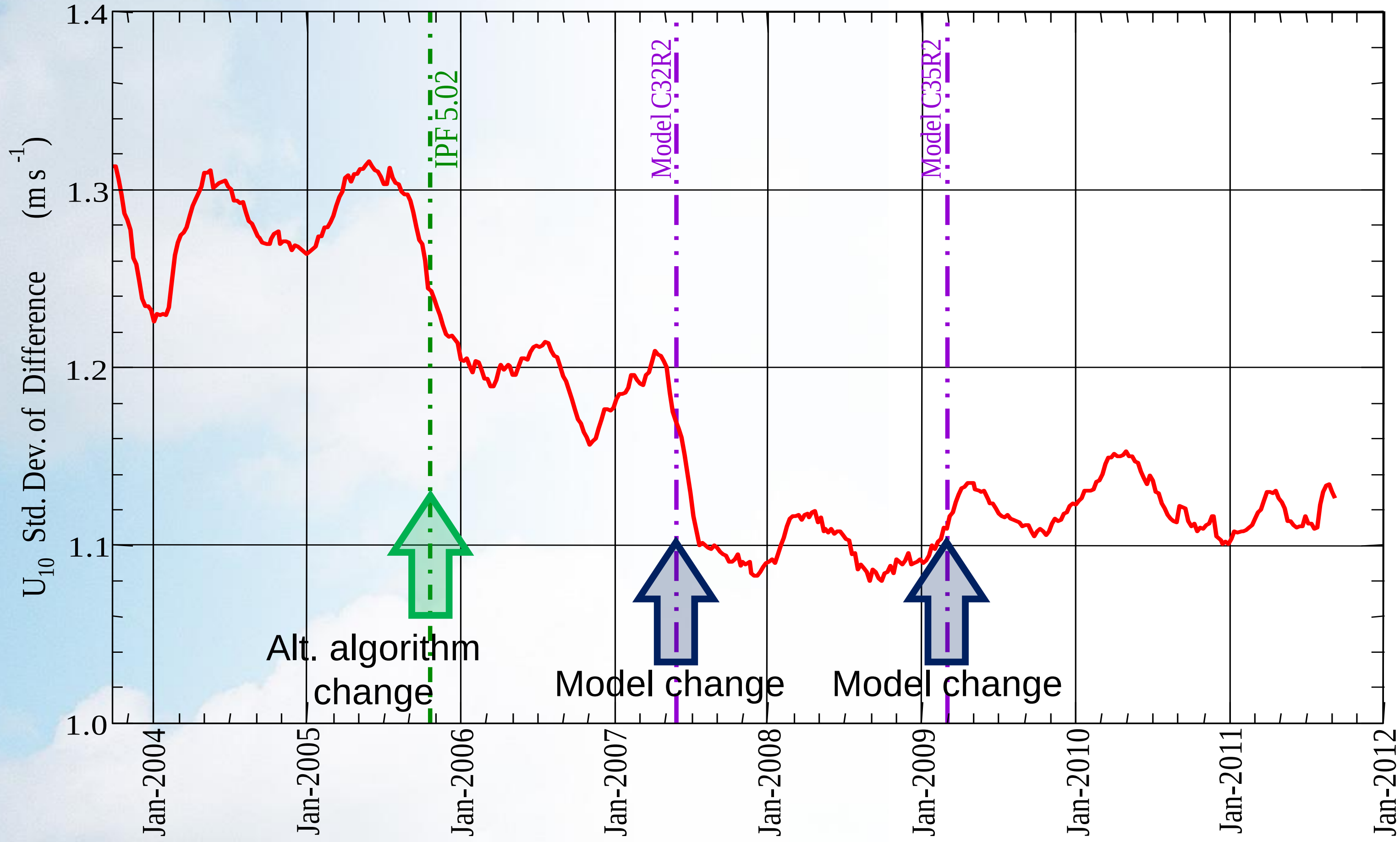




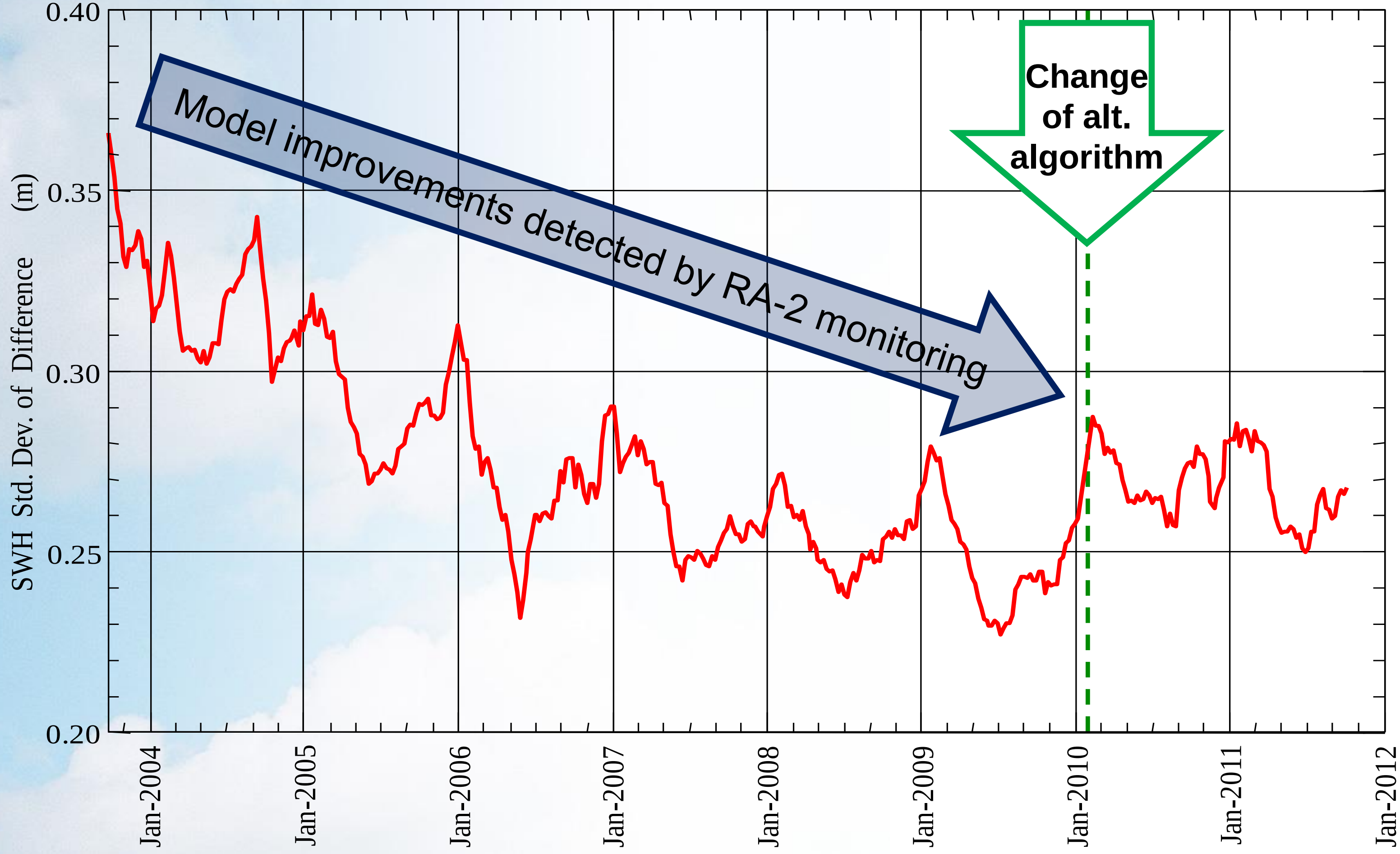
500 hPa

Assessment of model changes
&
Monitoring of model performance

Change Assessment: Change of SDD between ENVISAT RA-2 and ECMWF Model Wind Speed

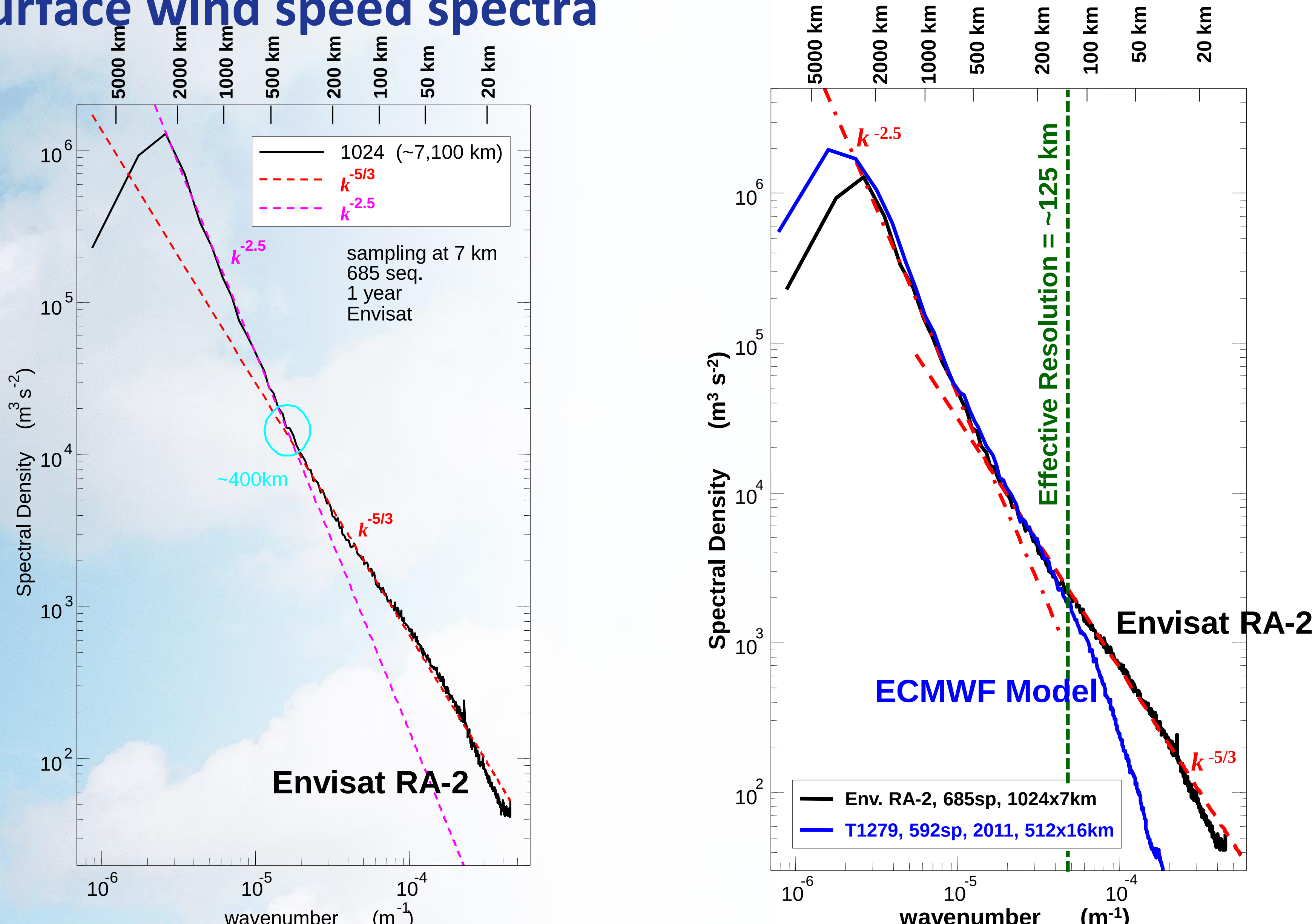


Performance Monitoring: Change of SDD between Envisat RA-2 and ECMWF Operational SWH

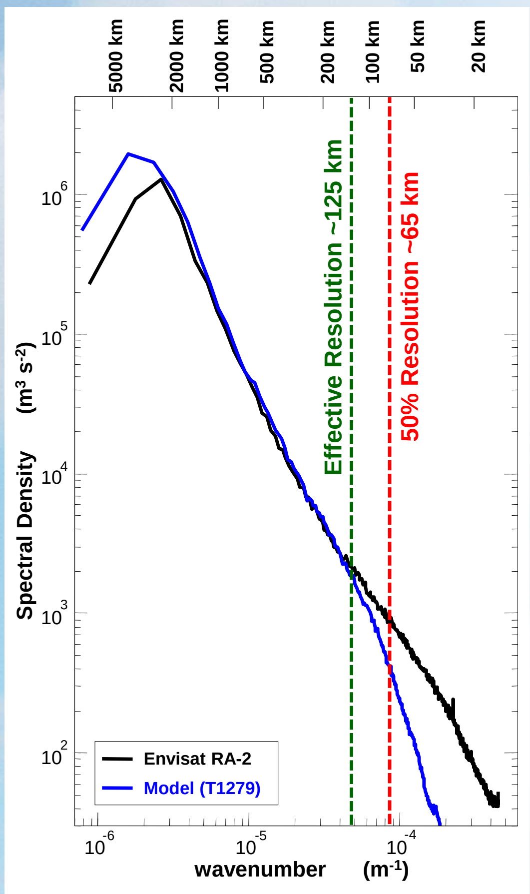


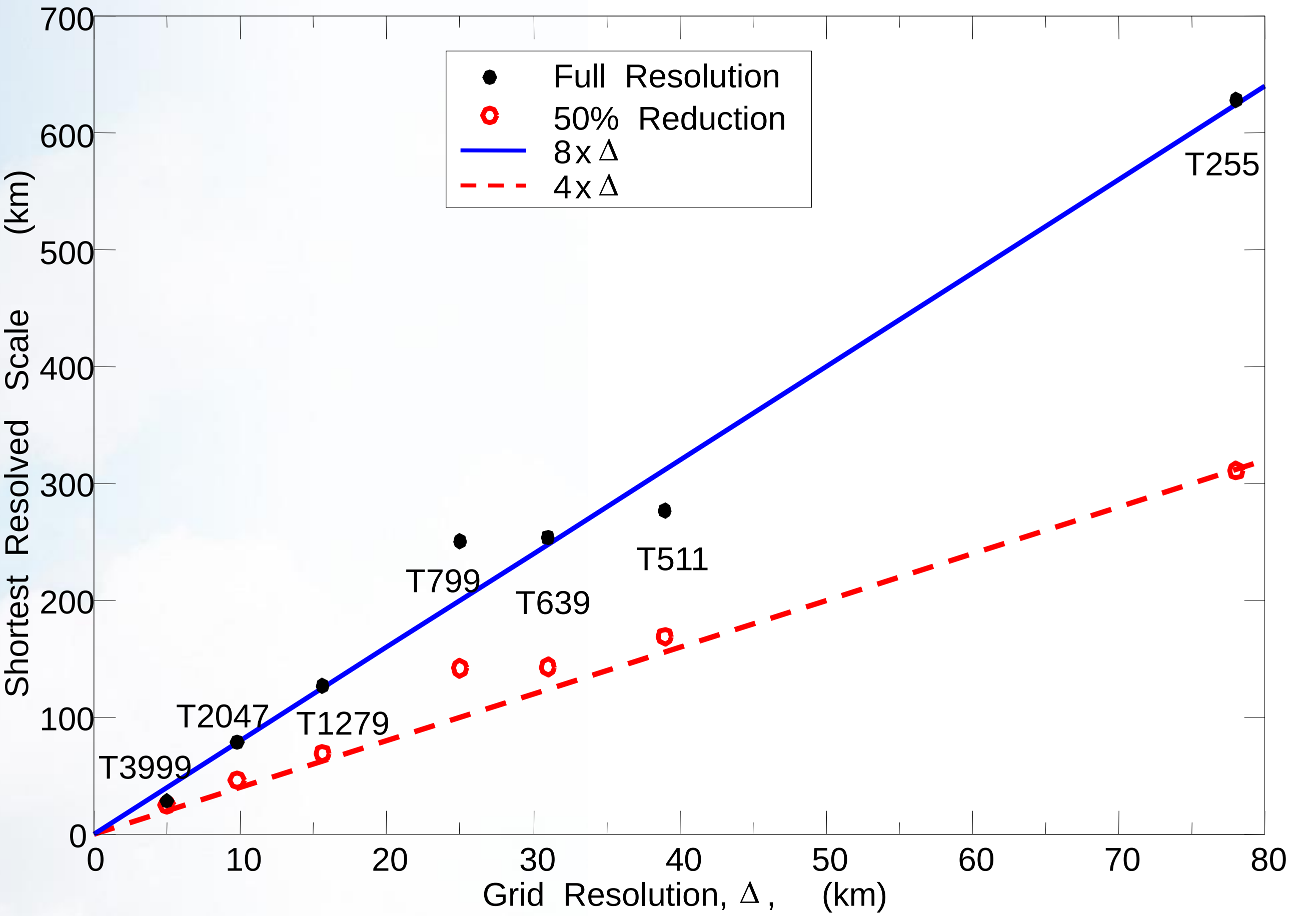
Effective Model Resolution

Surface wind speed spectra



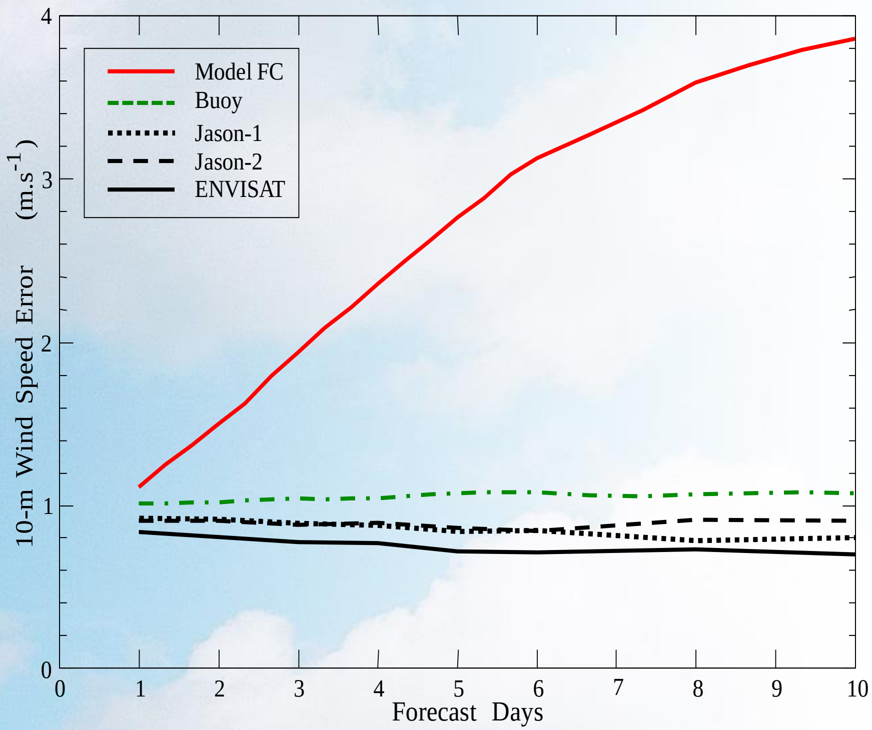
Effective Model Resolution

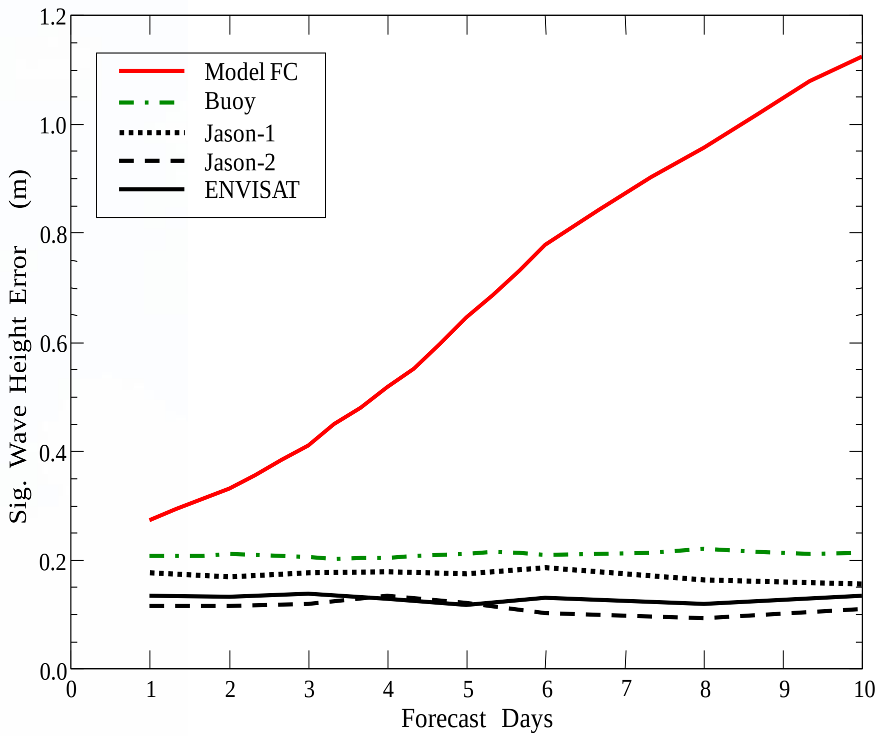




Error estimation

Random Error Estimation of Wind Speed & SWH using triple collocation technique





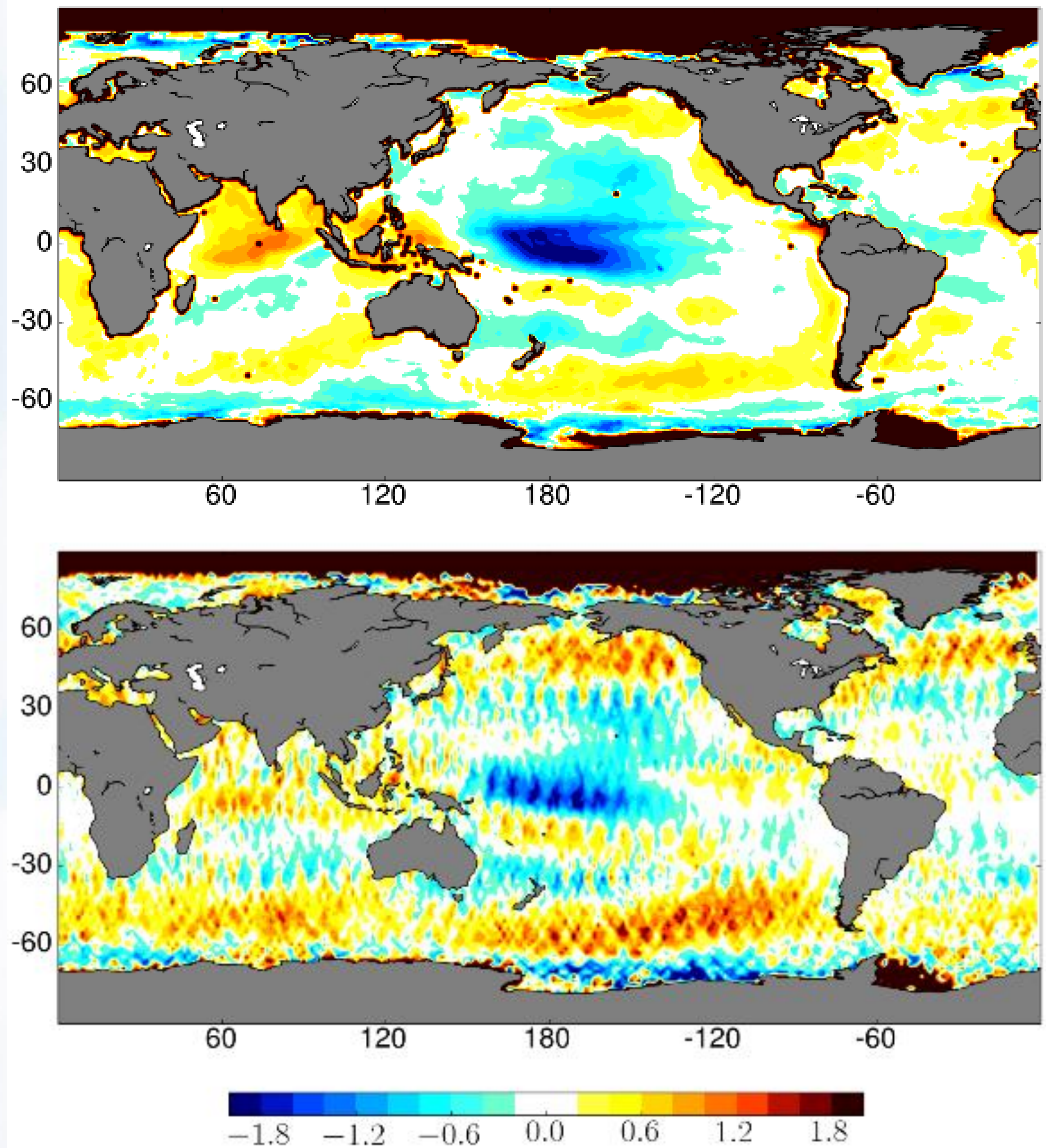
Long Term Studies

Trend of “zonal” winds between 1992 and 2010 according to:

Scatterometer

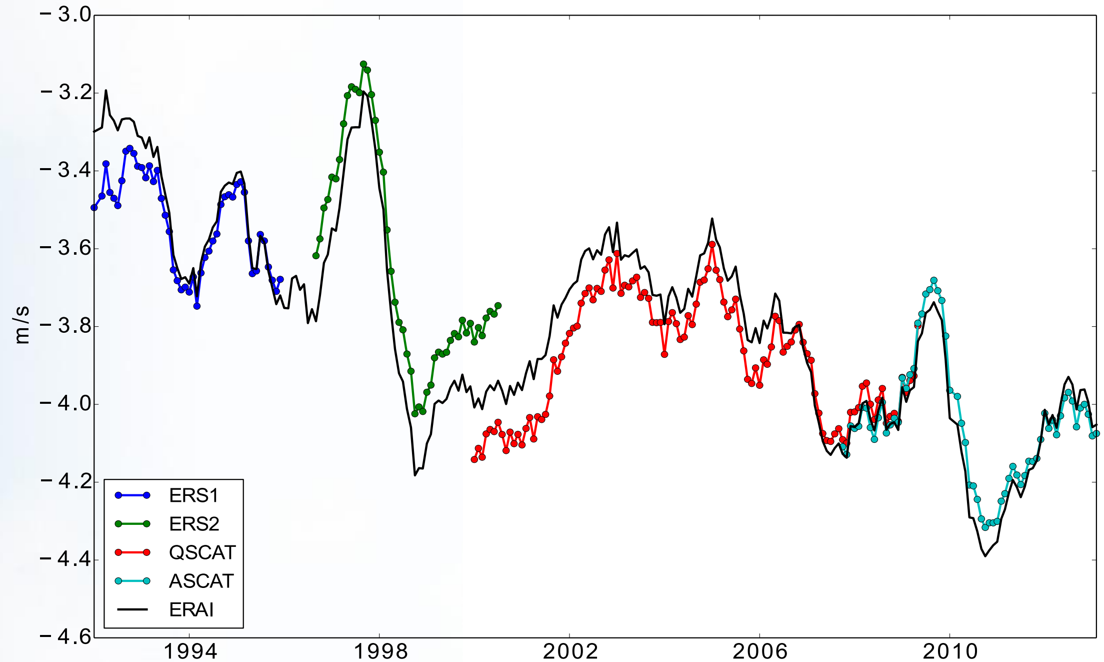
&

Altimeter



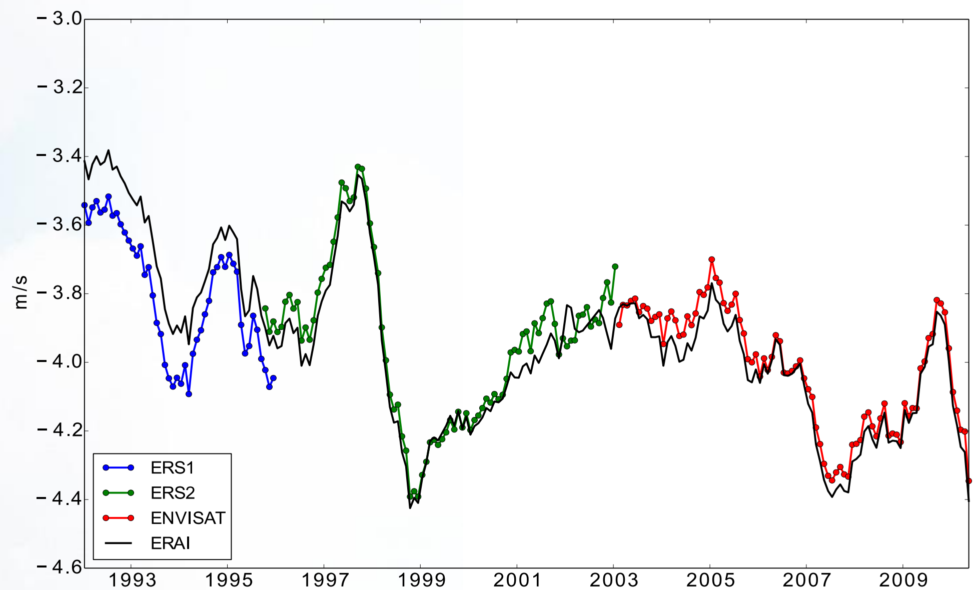
Mean "zonal" winds in Tropical Pacific basin according to:

Scatterometer



&

Altimeter



Concluding Remarks

Model – Satellite Data: 2-Way Benefit

- **Model wind and wave data are used for:**
  - Monitoring quality of satellite data.
  - Assessing changes in processing of satellite data.
  - Detecting anomalies in the data.
  - Cal/Val of new instruments/products.
- **Satellite wind and wave data are used for:**
  - Data assimilation.
  - Monitoring of model performance (inc. model resolution).
  - Assessment of model changes.
  - Use in reanalyses (assimilation and validation).
- **Error estimation.**
- **Long term assessments & climate studies.**

Synthetic Aperture Radar (SAR)

Outline

Scatterometer Winds

- ✓ The importance of scatterometer wind observations
- ✓ Scatterometer principle
- ✓ Data usage at ECMWF and their impact
- ✓ How we can improve the use and impact
- ✓ Concluding remarks

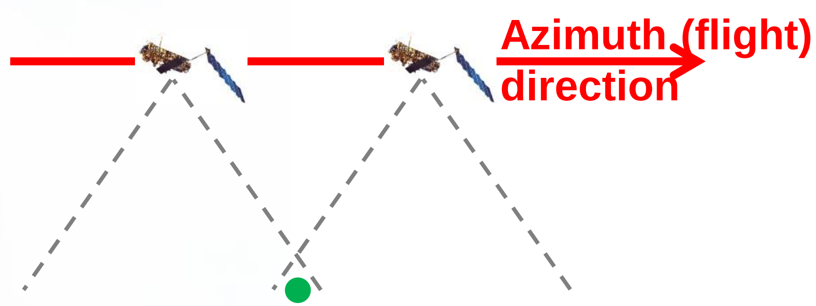
Altimeter Wind and Waves

- ✓ Introduction
- ✓ Verification and Monitoring
- ✓ Wave Data Assimilation
- ✓ Assessment of Model Performance (inc. Model Effective Resolution)
- ✓ Error Estimation
- ✓ Long Term Studies
- ✓ Concluding Remarks

Synthetic Aperture Radar (SAR)

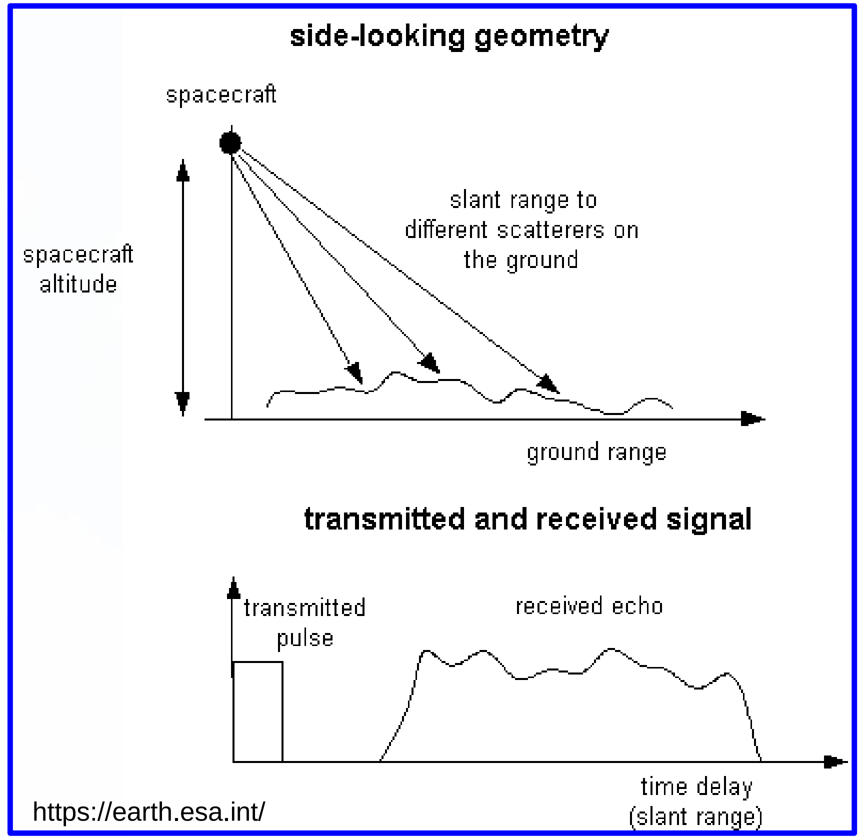
Synthetic Aperture Concept

- A radar system with a “synthetic” aperture simulates a “virtually” long antenna in order to increase azimuth resolution without increasing the actual antenna.
- The green target remains within the radar beam for the distance travelled by the satellite. The length of the synthesized antenna is equivalent to this distance. Synthetic Aperture Radar allows for a resolution of ~30 meters.

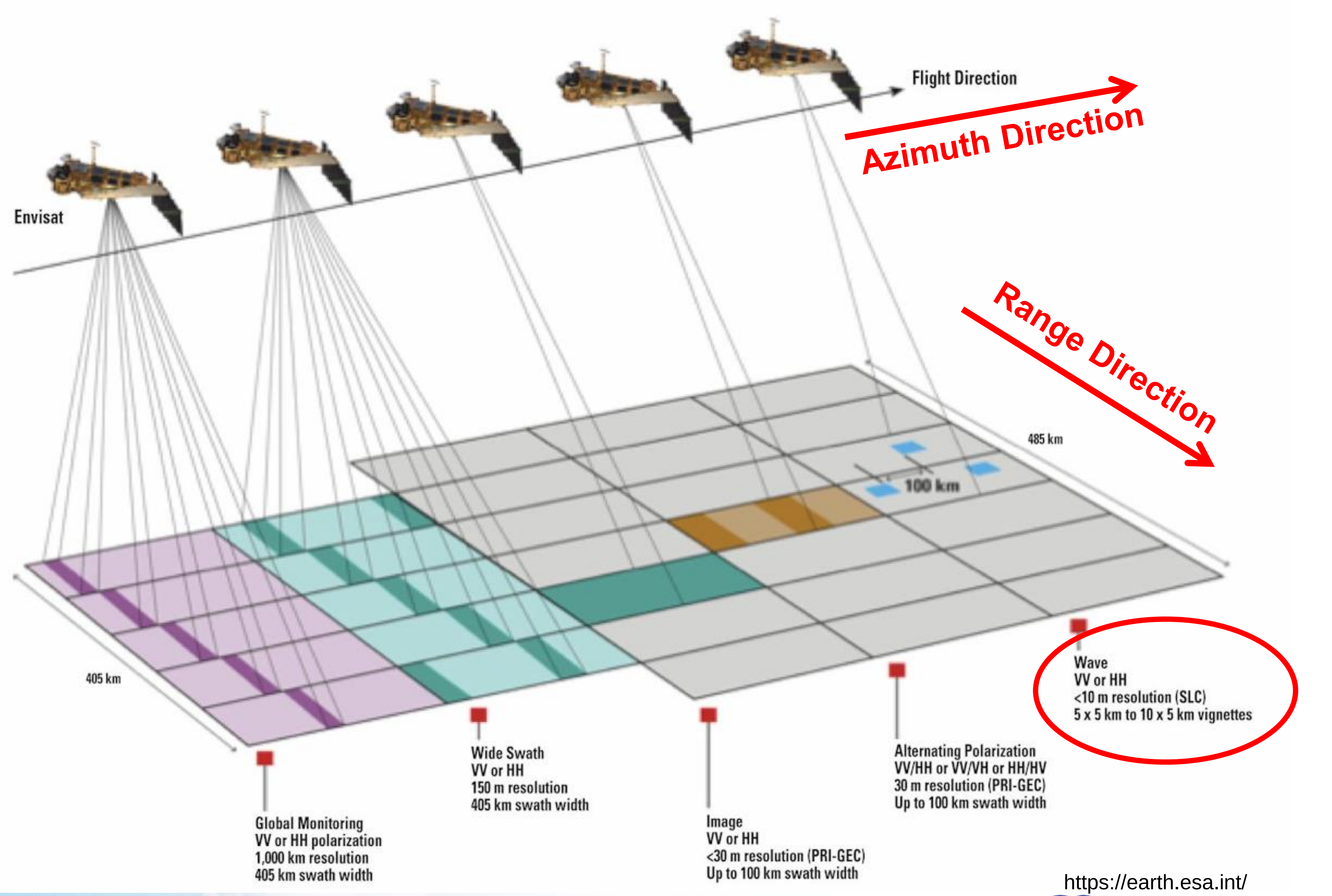


Synthetic Aperture Radar (SAR)

- SAR is a side-pointing radar that provides 2D spectra of ocean surface waves (wavelength and direction of wave systems).
- Measures distances in the “slant range” ➔ distortions.
- Water motion introduces further (nonlinear) distortions.
- 5 km x 6 (or 10) km images ➔ SAR image spectra.
- SAR inversion: ocean wave spectrum is retrieved from SAR spectrum using nonlinear mapping.

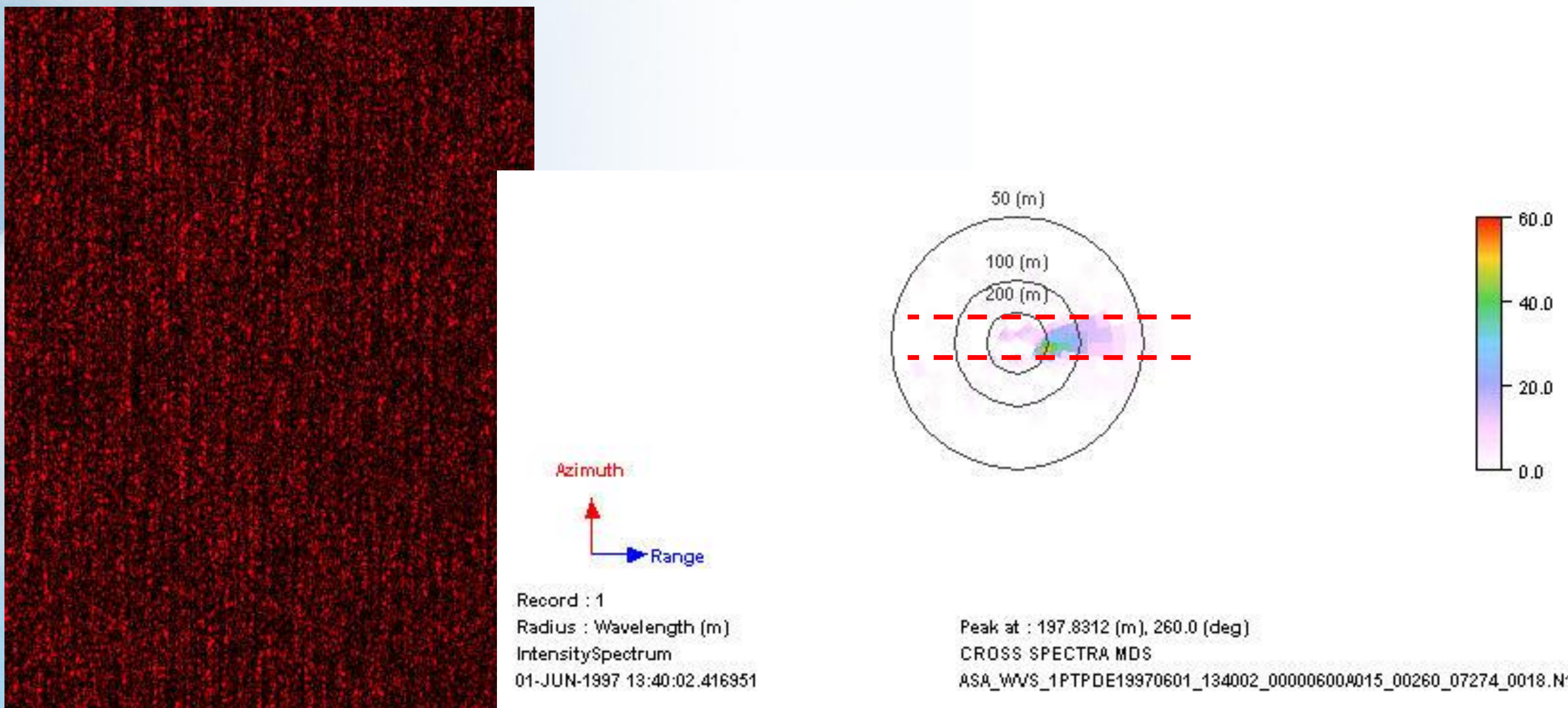


ENVISAT Advanced Synthetic Aperture Radar (ASAR)



https://earth.esa.int/

SAR Wave Mode Image & SAR Image Cross-Spectrum (Level 1b)



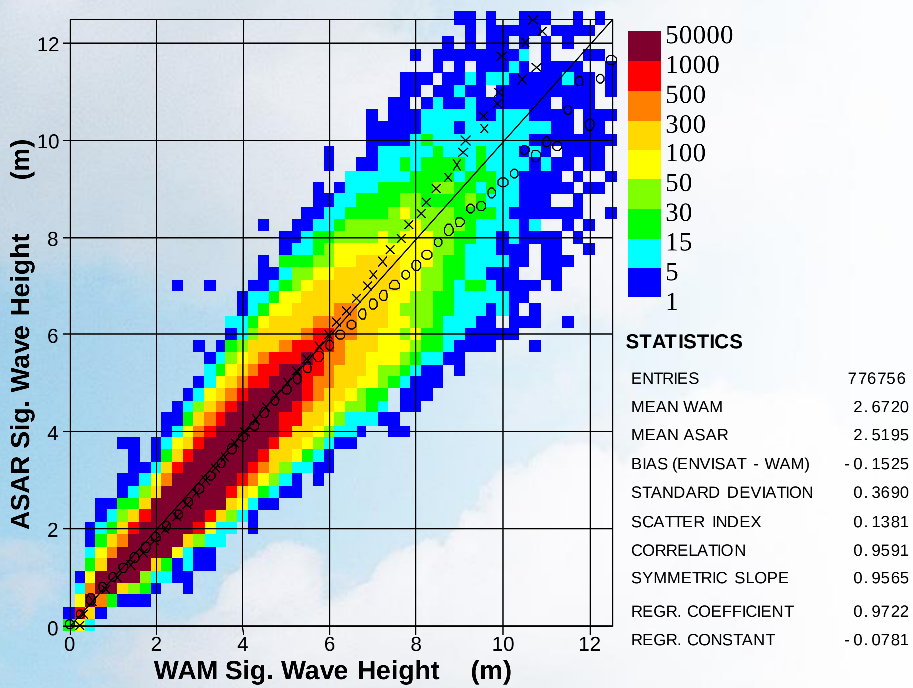
https://earth.esa.int/

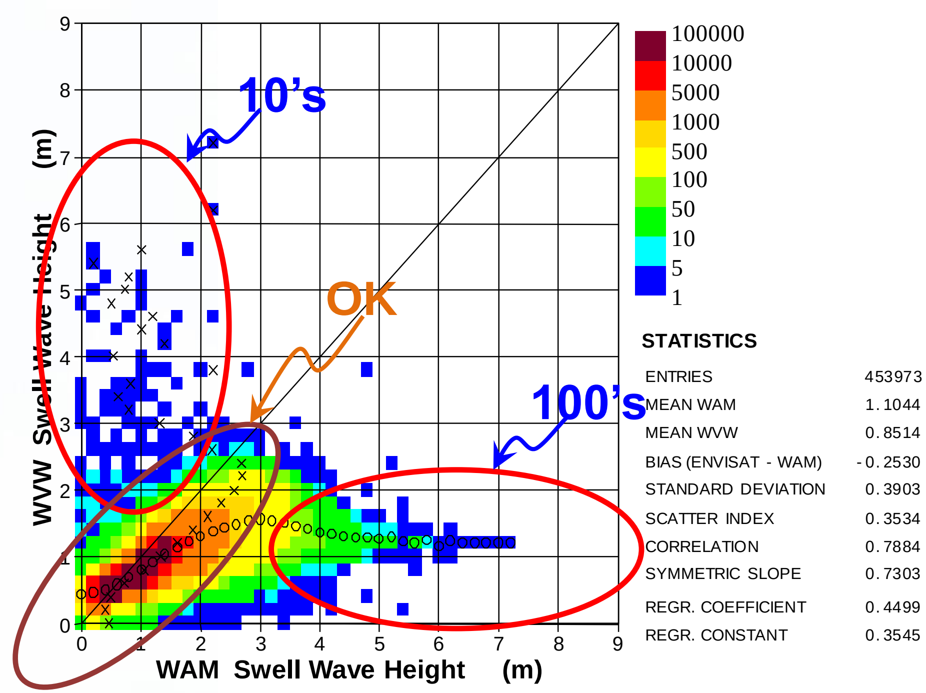
- Almost full Resolution in the range direction (30 m ~ 1000 m).
- Limited resolution in the azimuth direction (>~200 m).

Global comparison between ASAR and WAM model (2011)

Inverted L1b
(full spectrum)

L2
(within azim. cut-off)





ECMWF

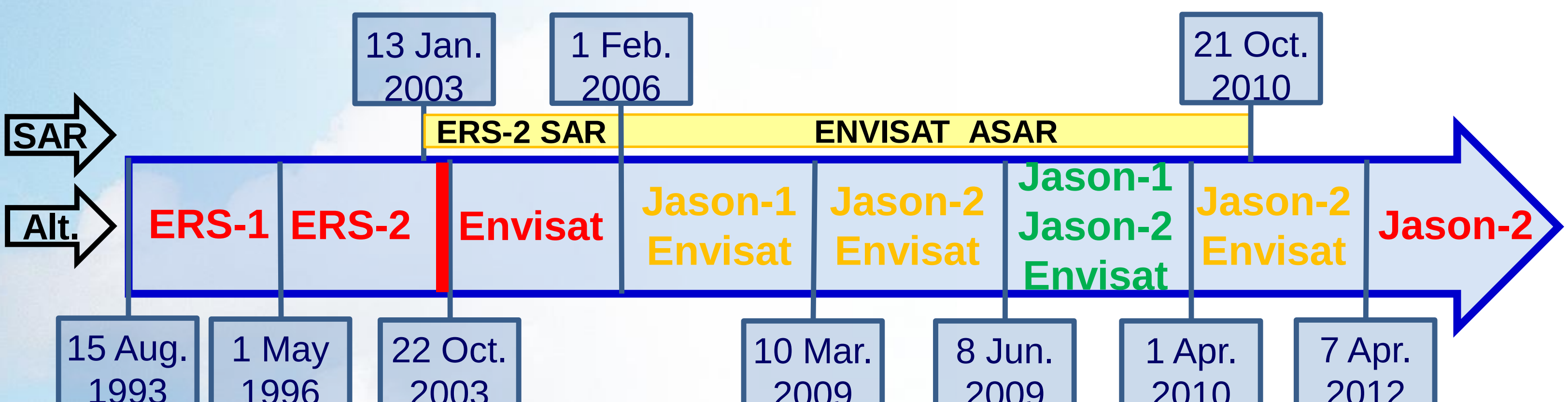
Assimilation of SAR Wave Data - Method

- Assimilation Method:
  - L1b SAR spectra are inverted to ocean wave spectra.
  - Ocean spectra are partitioned into wave systems which then paired with the corresponding systems in the model.
  - Simple OI scheme on integrated parameters of the systems.
  - Each partition is adjusted based on its analysis increment.

Assimilation of Wave Data

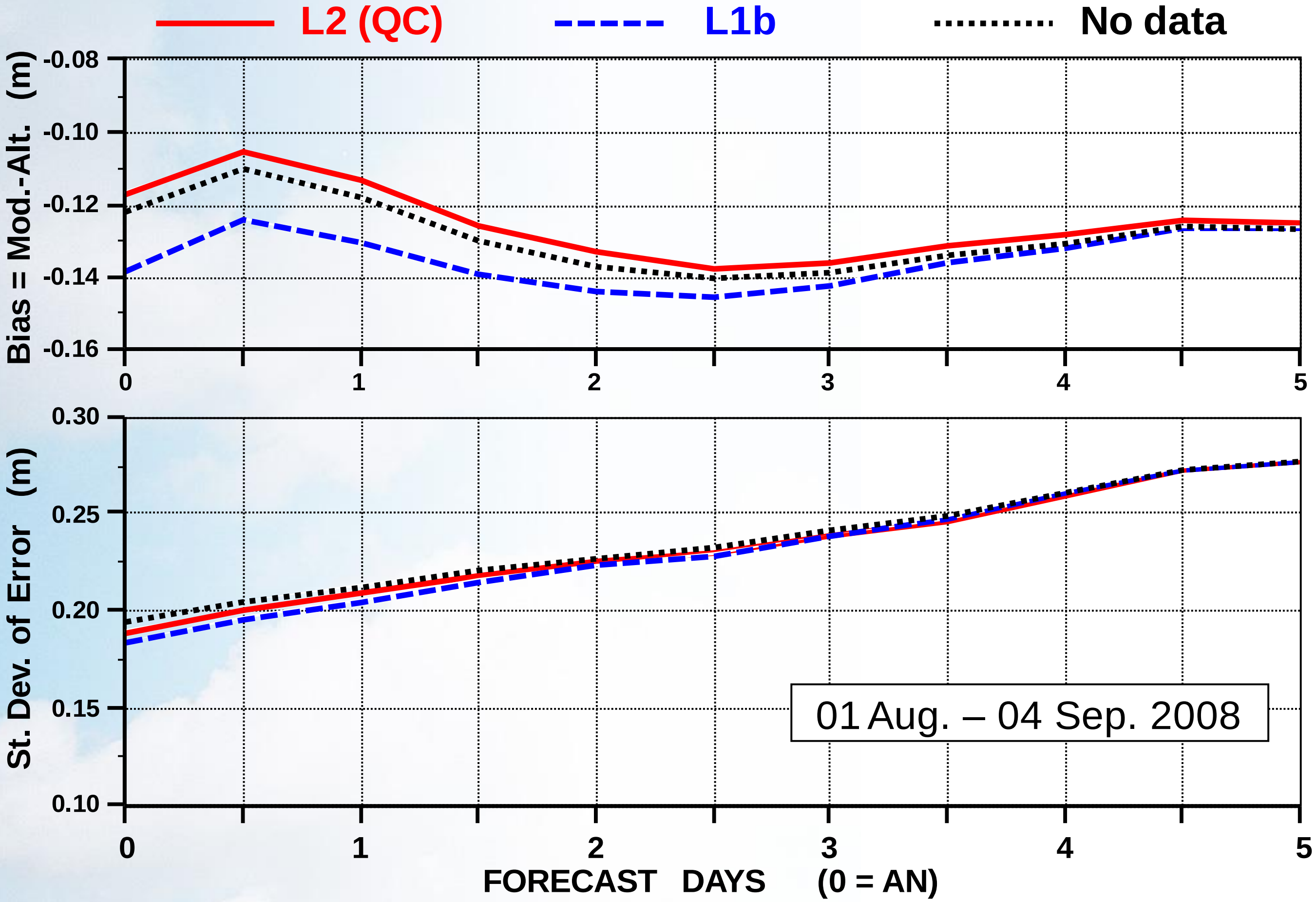
- NRT Altimeter (Ku) SWH operational assimilation at ECMWF:
  - ERS-1 URA, 15 August 1993 – 1 May 1996;
  - ERS-2 URA, 1 May 1996 – 23 June 2003;
  - ENVISAT RA-2 FDMAR, 22 October 2003 – 7 April 2012;
  - Jason-1 OSDR, 1 February 2006 – 1 April 2010;
  - Jason-2 OGDR, 10 March 2009 – on-going

- NRT SAR spectra operational assimilation at ECMWF:
  - ERS-2 SAR UWA, 13 January 2003 – 31 January 2006;
  - ENVISAT ASAR WVS, 1 February 2006 – 21 October 2010.



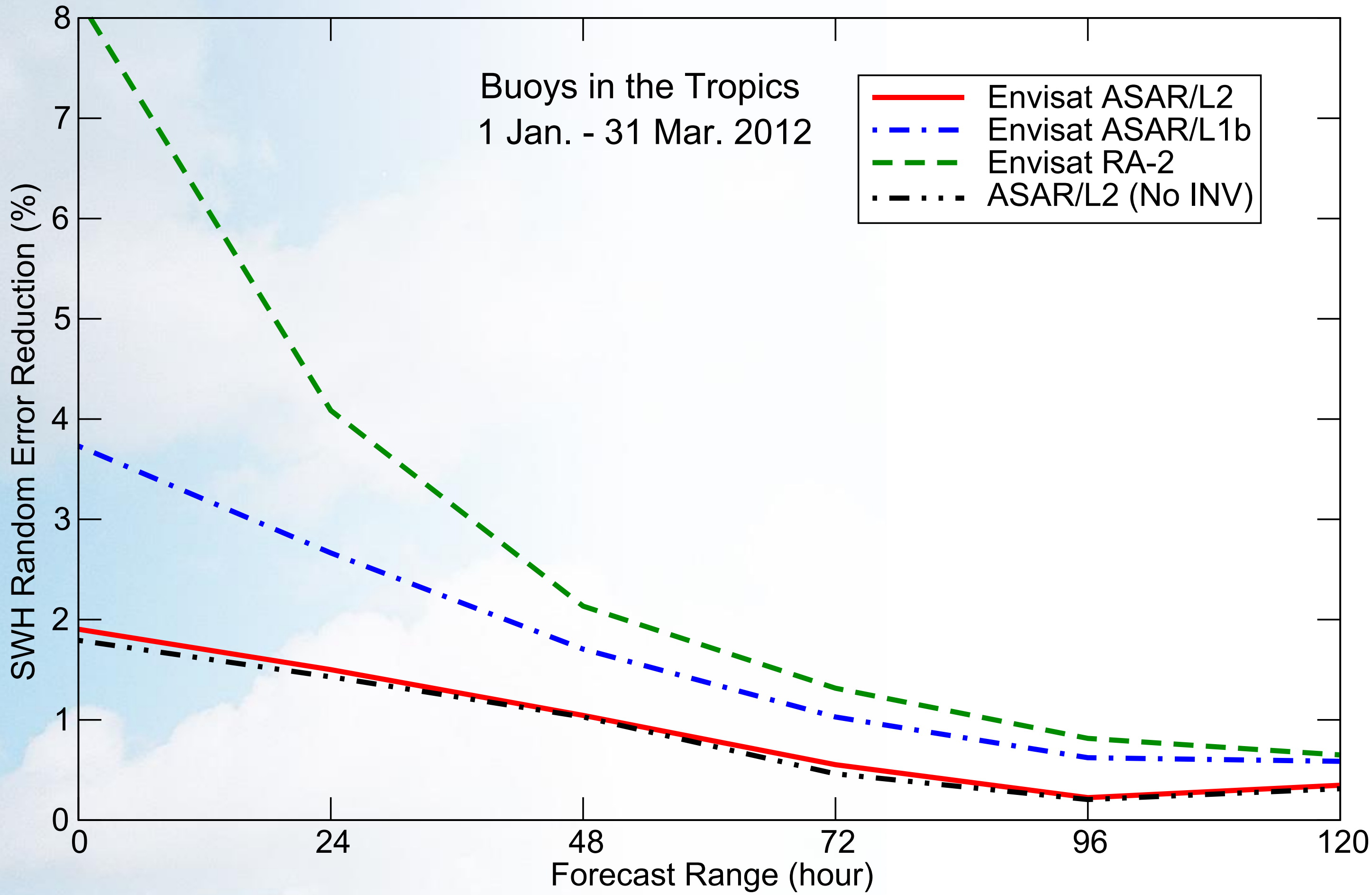
Impact of assimilating WM data on SWH bias and SDD in the Tropics

Verified against Envisat and Jason-1 altimeter SWH data.



SWH Error reduction Due to Assimilating WM (& RA-2 SWH) Products

Verified against in-situ measurements in **Tropics**



Conclusions (SAR)

- Fast delivery ENVISAT ASAR Wave Mode products:
  - L1b → inverted in-house → operationally assimilated.
  - L2 → already inverted → difficulties in assimilation.

- Assimilation of ASAR WM L1b product leads to positive impact on the model forecasts (up to 4% error reduction and last for 2-5 days).

- Assimilation of ASAR WM L2 leads to rather limited impact (<2% error reduction).

- Similar work will be carried out for Sentinel-1.

Definition of Difference Measures

- Systematic error (Bias) is:

$$\text{Bias} = N^{-1}\sum_{i=1}^{N}(x_i - T_i) = \bar{x} - \bar{T}$$

- Root mean square difference (RMSE):

$$\text{RMSE} = \sqrt{N^{-1}\sum_{i=1}^{N}(x_i - T_i)^2}$$

- Standard deviation of the difference (SDD):

$$\text{SDD} = \sqrt{N^{-1}\sum_{i=1}^{N}(x_i - T_i - \text{Bias})^2}$$

$$\text{SDD} = \sqrt{N^{-1}\sum_{i=1}^{N}(x_i - T_i)^2 - \text{Bias}^2}$$

- Scatter index (SI):

$$\text{SI} = \text{SDD} / \bar{T}$$

- $\boldsymbol{x}$ = altimeter data set, $\boldsymbol{T}$ = reference data set (e.g. in-situ), $\boldsymbol{N}$ = total number of collocations

ECMWF